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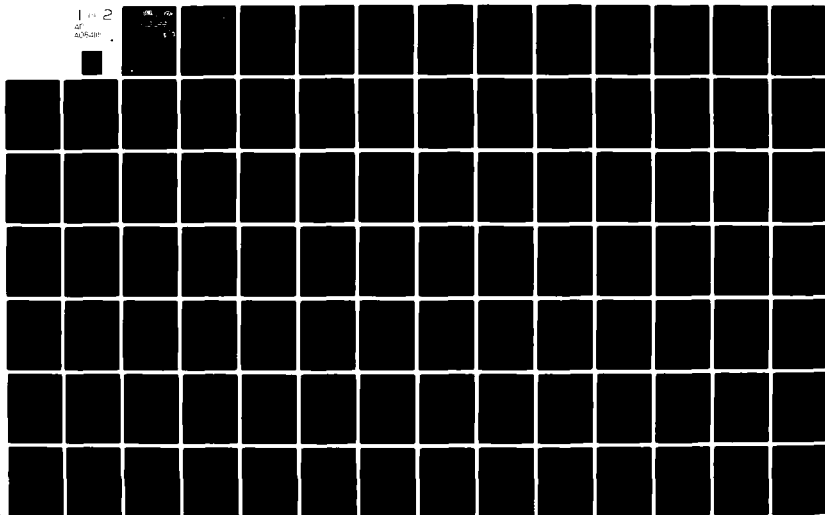
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AIR-TO-AIR HELICOPTER FIRE CONTROL EQUATIONS AND SOFTWARE GENERATION

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January 15, 1980

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ABSTRACT

Fire control equations suitable for use in a helicopter air-to-air gunnery engagement are developed. Maximum use is made of existing software from the Closed Loop Fire Control System (CLFCS). New target state estimator, ballistics, and gun order modules are developed to account for target motion effects. The resulting software was coded and run in the CLFCS fire control computer, and made to interface with a modified Multiweapon Fire Control System.

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SECTION 1

INTRODUCTION

The principle objective of this program is to develop a set of fire control equations which are suitable for use in a helicopter air-to-air engagement. The details of this design are explained in Section 2 and the resulting software is documented in Section 4. Certain other analysis tasks relating to target motion and overall system configuration are documented in Section 3. The firing rate analysis (Section 3) is notable among these tasks as it provides the mathematical foundation for the dual rates of fire (750 and 1500 shots-per-minute) to be used in testing this fire control system.

In order to prove the feasibility of this concept and to provide a test bed at minimal development cost, maximum use has been made of existing software from the Closed Loop Fire Control System (CLFCS). As shown in Figure 1, new software was written to run in the CLFCS Computer Interface Unit (CIU), which consists of a CDC 469 minicomputer plus I/O. It assumes the existence of the Inertial Measurement Unit (IMU) and vertical reference unit from the CLFCS as inputs to be used by the Aircraft State Estimator (ASE), the major piece of CLFCS software which has been left intact and used "as is". The ASE provides filtered values of ownship's velocity and a vertical vector for use in the new air-to-air fire control equations.

The new software developed for this project functionally can be broken into two pieces: the Target State Estimator (TSE), and the ballistics and gun order modules. The TSE includes not only the estimation of target position, velocity, and acceleration, but also provides total software track control including a filtered manual track mode plus fade in to a rate-aided track mode. The gun order module computes the proper lead angle plus a gun turret rate feed forward signal. A new executive routine was also developed to handle the increased I/O, as well as subroutine calls associated with the new functions. This new software is written to interface with the Stabilized Optical Sight (SOS) from the Multiweapon Fire Control (MWFC) helicopter, as well as the laser rangefinder and air data package from that same aircraft.

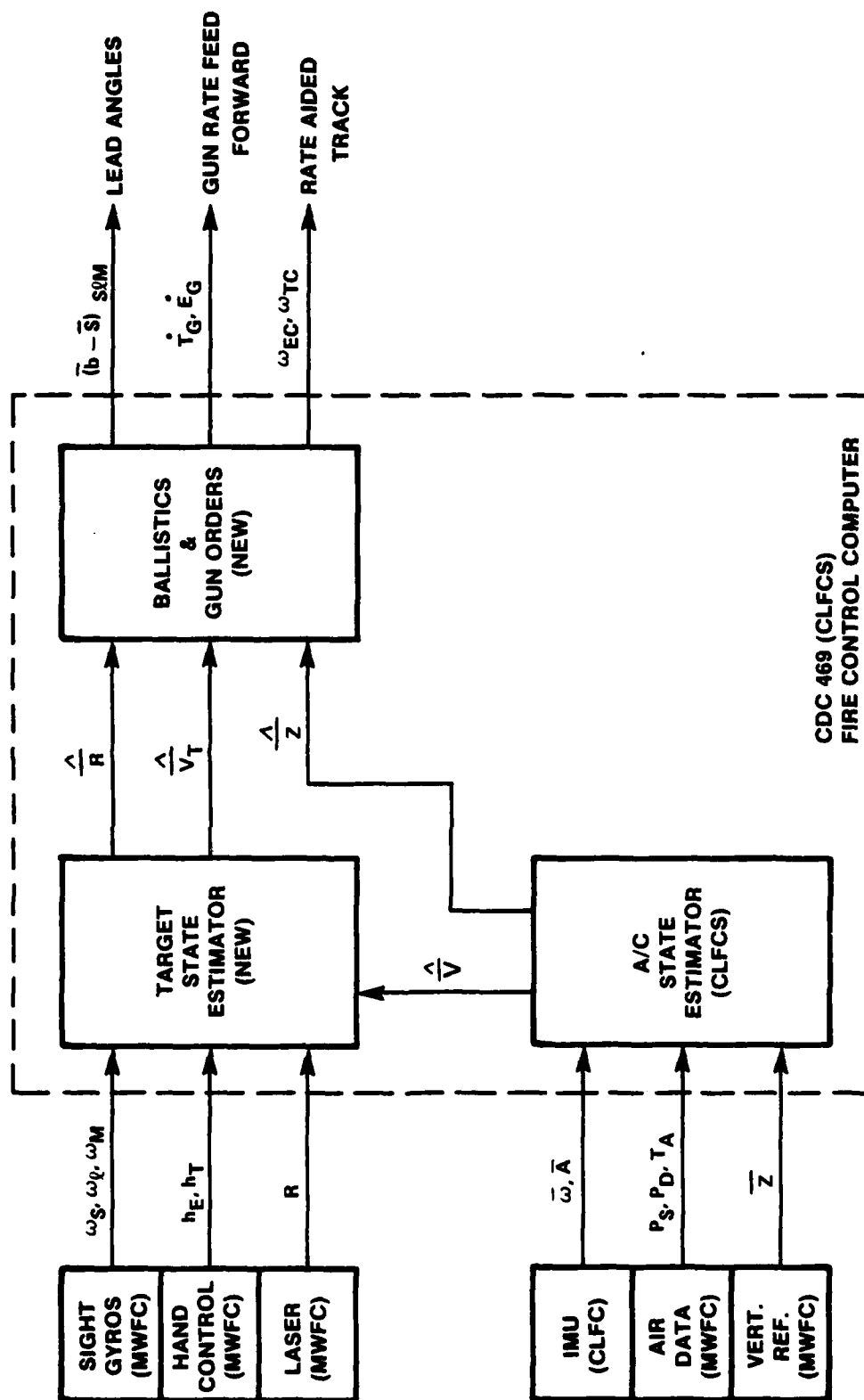


Figure 1. Air-to-Air Fire Control Software

SECTION 2

FIRE CONTROL EQUATIONS

This section will outline the theory and explain the functional relationships of the fire control equations which have been developed for air-to-air helicopter engagements. For further information on the detailed implementation of these equations in the CDC 469, refer to Appendix A, Air-to-Air Fire Control Software Specification, and Section 4, Software Documentation.

TARGET STATE ESTIMATOR

The TSE is the heart of the air-to-air fire control system, and has been designed as a constant gain decoupled Kalman filter. The TSE computes in the rotating line of sight coordinate frame, with axes designated by s, l, m, and defined by

- s: Pointed along the line-of-sight to the target
- l: Normal to s, left and nominally horizontal (for zero sight elevation)
- m: Normal to s and l, nominally vertical

The function of the TSE is to produce filtered values, or estimates, of the target position ($\hat{R}_s, \hat{D}_l, \hat{D}_m$), velocity ($\hat{V}_{Ts}, \hat{V}_{Tl}, \hat{V}_{Tm}$), and acceleration ($\hat{A}_{Ts}, \hat{A}_{Tl}, \hat{A}_{Tm}$) using the measured values of range, R_m , angular rate of the LOS W_s, W_l, W_m and the gunner's track stick thumb button inputs (h_E, h_T). The range measurement comes from the laser or the manual range pot input, and the LOS rates come from three gyros mounted on the SOS sighthead. In addition, the TSE uses filtered values of ownship's velocity ($\hat{V}_s, \hat{V}_l, \hat{V}_m$) from the existing ASE code.

The TSE is actually composed of three separate filters: range, traverse, and elevation. Equivalent analog block diagrams of these digital filters are given in Figures 2, 3 and 4. The exact implementation of the digital integrations is specified in Appendix A, Sections 7.4, 7.5, 7.6, and 7.7, where it is seen that the integrations are separated into two phases: estimation and extrapolation. The estimation actually corresponds to a time 0.3 of the way into the 1.30 second update interval in an effort to compensate for computational delays.

Note that the three channels are symmetrical, each having a noise filter in the position error channel (measurement residual), followed by three integrators. The integrator outputs contain the target's acceleration, velocity, and position respectively in the axis of that channel. The input to each integrator is fed by a "Kalman" gain (e.g., K_{Ps}, K_{Vs}, K_{As}) times the filtered channel residual. These Kalman gains are the filter bandwidth in radians per second times the update interval, 1.30 second. The gains that have been selected correspond to a 3 R/S bandwidth for the position estimates, and 4.5 R/S for the velocities and accelerations.

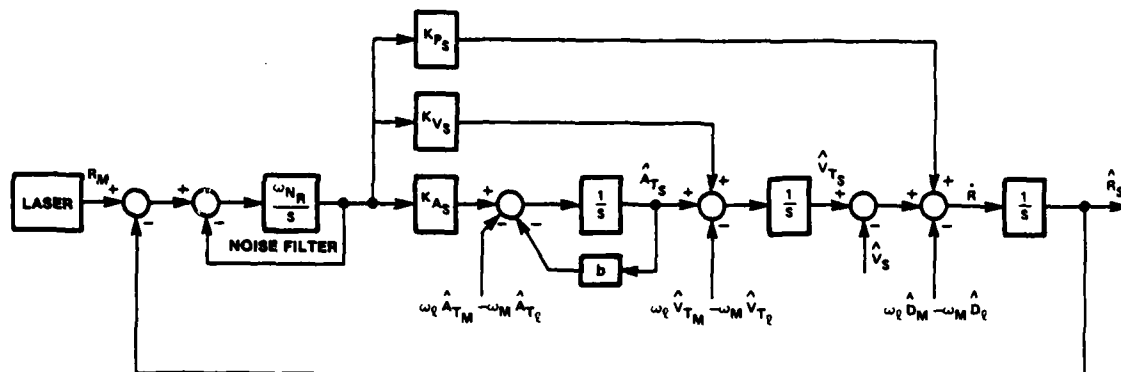


Figure 2. Range Filter

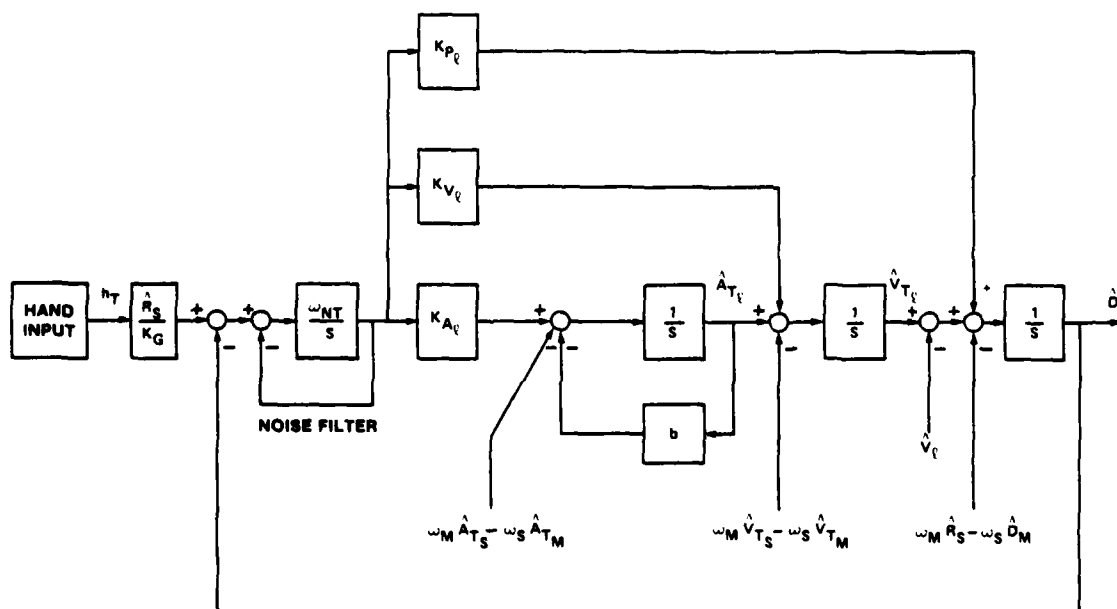


Figure 3. Traverse Filter

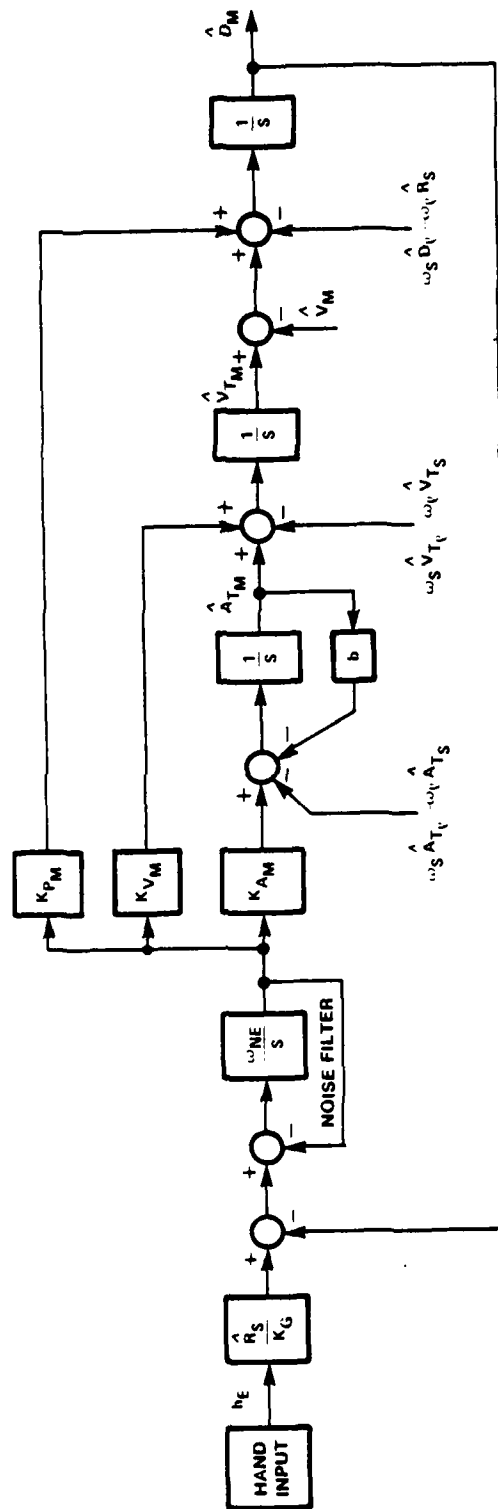


Figure 4. Elevation Filter

The acceleration integrator has a small feedback around it ($b = 1/10$) which comes from modeling the expected target dynamics as having a nearly constant acceleration with a 10 second time constant.

Note that the input to each integrator also has cross channel coupling terms which are cross products of the LOS angular rate (W_s, W_l, W_m) with the state vector component associated with that integrator. These terms are the Coriolis terms, or apparent rates of change that must be subtracted out so that the slm computing frame is effectively stabilized against sight inertial rotations.

A final input to the TSE is ownship's velocity ($\hat{V}_s, \hat{V}_l, \hat{V}_m$). This is subtracted from the estimated target velocity ($\hat{V}_{sT}, \hat{V}_{lT}, \hat{V}_{mT}$) before the final integration so that the position vector ($\hat{R}_s, \hat{D}_l, \hat{D}_m$) gives the relative range and off boresight of the target with respect to ownship's position.

INITIALIZATION AND RANGE COASTING

Before the gunner pulls the ACTION switch, the computer executes the Aircraft State Estimator equations and also provides manual mode sight control as described in Section 2. The request for fire control computations to begin is given by the gunner pulling ACTION.

By this time the gunner should have started the laser and established a good track such that valid laser measurements are being received. The computer then waits for two different range measurements to be made before initializing the TSE filters. The two range measurements are used to initialize range rate and thus minimize the initial filter transient. The two measurements must be received within 1.1 seconds of each other in order to ensure an accurate estimate of range rate. This TSE initialization is specified in Section 7.3 of Appendix A.

Section 7.2 of Appendix A also specifies a Range Coasting Logic for use in the ACTION mode. This provides the TSE range filter with an updated range measurement during laser interpulse periods, and during periods up to nine seconds in duration when no valid laser range data is obtained. This "coasting" is accomplished by integrating the estimated value of range rate using the last valid range measurement as an initial condition.

TRACK LOOP

Operator control of the SOS is done entirely through the fire control computer when a switch in the battery access compartment of the MWFC aircraft is in the "CIU" position. The switch must be in this position for proper fire control operation. The other switch position is marked "SOS" and routes the operator inputs through the normal sight electronics, including a lag-lead tracking filter which gives a regenerative track feel to the operator and results in very accurate track at lower rates. The reason for providing the "CIU" position is the necessity for eliminating the track filter when the TSE is running and rate-aided track is in effect to provide operator assistance at the higher tracking rates encountered in air-to-air moving target engagements (ACTION mode). This must be done because the TSE elevation and traverse channels are designed under the assumption that the operator's hand station inputs are proportional to the commanded rate (which is linearly related to

observed angular error by the track loop gain $K_G = 6 \text{ rad/sec.}$). But with the filter, the hand station commands must be roughly proportional to acceleration because of the filter's integration effect. The filter provides much the same type of regeneration during manual track that the rate-aided track is designed to supply in the ACTION mode. Thus, the filter must be eliminated during ACTION mode but must be kept in the Non-ACTION manual mode to provide accurate manual track.

Figure 2 shows diagrammatically how the air-to-air track loop is implemented. Note that the gunner is modeled as closing the track loop with gain K_G . This corresponds to him observing an angular position error $\Delta \theta$ and outputting a proportional hand control voltage \bar{h} . This simple closure is a valid model during rate-aided track operation when the gunner is required to only make corrections to the rate-aided track signal. The gain used corresponds to a 6 radian/second track loop closure.

Note that before the hand control signals \bar{h} are input to the TSE, they are divided by K_G to obtain $\Delta \theta$ in radians, then multiplied by \hat{R}_s , estimated range, to construct an input proportional to target off-boresight position in meters.

Two Stage Gain

In order to provide good resolution for accurate track a low track stick gain is needed. But for initial acquisition a large gain is needed to generate high rates. These two requirements are satisfied by the two stage gain which is specified in Section 2.3 of Appendix A. It is expected that during ACTION mode the rate-aided track signal will be accurate enough that the gunner will always be within the low gain slope. The constant K_G has been sized under this assumption.

Track Filter

The track filter is modeled after that used in the SOS hardware. The equations which are specified in Section 4.5 of Appendix A correspond to the transfer function:

$$G(S) = \frac{\frac{S}{.98} + 1}{\frac{S}{.17} + 1}$$

Note that this filter has unity low frequency gain, and is effectively an integrator in the region of target dynamics (.17 R S to .98 R S). In addition, the hardware anti-aliasing filters (20 R S) on the hand control inputs provide a high frequency roll-off which closely match that of the SOS filter.

This filter is used primarily in the Non-ACTION mode; but also during ACTION while waiting for the second laser range word to be received.

Fade In and Fade Out

After the second laser range word has been received in the ACTION mode the rate-aided track signal plus linear hand control connections are computed as diagrammed in Figure 5 and specified in Section 7.8 of Appendix A. At this time fade in and fade out signals are computed as specified in Section 7.12 of Appendix A. Both fades are completed in a linear manner over an interval 0.8 seconds long. The fade out is applied to the filtered hand control inputs (called W_{ECH} and W_{TCH} in the Appendix), while the fade in is applied to the rate aided track plus operator correction signals (W_{EC} and W_{TC}). The net effect is a smooth, constant gain transition between the two modes of operation.

The fade in is also applied to the turret lead angles and rate feed forward signals.

BALLISTICS

The air-to-air fire control computes time-of-flight and gravity drop based on future target position, assuming a constant target velocity. This first order prediction is done using a target velocity which has been generated from a filtered value of target acceleration in the TSE, and is felt to be the best compromise between smooth prediction and short response time.

The time-of-flight and future range are calculated iteratively since each is a function of the other, according to the logic of Section 7.9 in Appendix A. The BRL time-of-flight (T_F) equations are modified only very slightly such that only three quarters of the iteration-to-iteration change in T_F is used in the new future range calculation. This is done to ensure the stability of the iterations under all conditions, and has a small effect on convergence rate.

The logic is set up to require a minimum of two iterations to ensure accuracy. A maximum of five iterations is imposed as a further safeguard against nonconvergence. Normal termination of the loop is when the change in T_F is less than 1.5 milliseconds. Simulation and flight test data show between two and three iterations are normally needed to meet this criterion.

Gravity drop is added to the future range after the T_F iterations have converged, as specified in Section 7.10.1 of Appendix A. This formula represents a curve fit which results in negligible errors for R_F within the region of curve fit, $300 < R_F < 2000$ meters. Since the fit quickly deviates outside of this region, gun fire is inhibited for $R_F > 1999$. No such inhibit is used for $R_F < 300$, since the fit is better here, and also due to the large angular target size at close range.

LEAD ANGLE CALCULATION

The turret lead angle is computed in two steps as specified by Sections 7.10.2.1 and 7.10.2.2 of Appendix A. The first step is to compute the unit vector (b_s, b_l, b_m) which points in the desired gun direction. The equations specified were derived by setting the total projectile velocity vector (gun impulse plus aircraft velocity) parallel to the future range vector which has been computed in the ballistics section. A closed form solution to this condition is analytically very difficult; however, the iterative solution specified is straightforward and not computationally difficult. The calculations involve iteratively computing the gun vector as a function of total muzzle velocity, then total muzzle

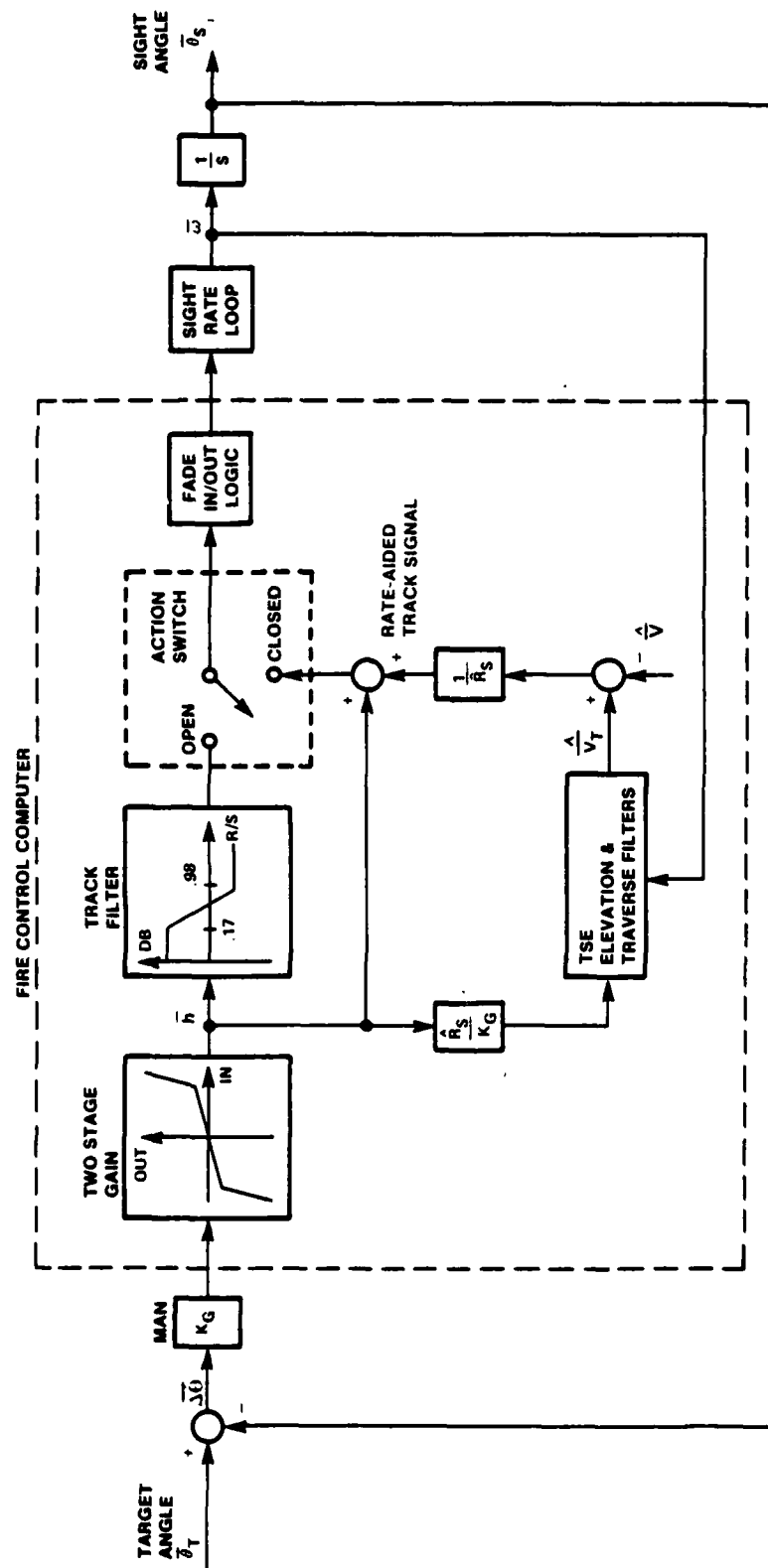


Figure 5. Air-to-Air Track Loop

velocity as a function of gun direction. Four iterations are specified, and only $\frac{1}{2}$ the change in gun vector is used to guarantee stability of these iterations.

The gun lead angle is then computed in line-of-sight coordinates by simply subtracting the sight direction, \bar{l}_s , from total gun direction (b_s, b_l, b_m), and then rotating to the aircraft coordinates in which the turret operates.

RATE FEED FORWARD

Turret rate feed forward commands are calculated to take advantage of the high bandwidth turret rate loop to remove most of the dynamic servo following error that results from the lower bandwidth position loop following the lead angle command. The equations are specified in Section 7.11 of Appendix A. They have been derived to calculate the sum of line-of-sight rate and lead angle rate in the turret coordinate system. Lead angle rate has been approximated by the assumption of a constant velocity target.

ALTERNATE MODES

Two backup modes have been designed to provide a degraded fire control solution in case the laser ranger is unavailable, or for testing without the laser. These modes are entered by selecting the TEST position on the NORMAL/TEST switch, and the desired mode on the TEST 1/TEST 2 switch.

TEST 1 is the most complete backup mode, as it simply substitutes the range value from the range pot for the laser range, and sets the "new range data bit" so the TSE and fire control continue as normal.

TEST 2 is a degraded mode which also reads the range pot instead of the laser. However, no rate-aided track is computed in this mode. In addition the TSE is not executed, and lead angles are computed assuming no target motion. This mode is specified in Section 8.0 of Appendix A.

SECTION 3

SYSTEMS ANALYSIS

FIRE CONTROL SYSTEM MATHEMATICAL MODEL

A digital computer program known as AIRSIM (Air-to-Air Simulation) has been developed to simulate the dynamics of an air-to-air engagement, and in particular the detailed performance of the air-to-air fire control system. AIRSIM contains a faithful model of the fire control equations, and was used extensively during the design phase to evaluate their performance in order to validate and debug the design concept. This was done long before the actual software was coded and ready for systems integration and functional testing.

AIRSIM is written in FORTRAN and runs on a PDP 1134 computer. It interfaces with a plot routine and Tektronix plotter and hard copy unit so that time histories of 37 variables of interest are available for analysis.

The program structure is shown in Figure 6 in the form of a top level flow chart. Note that after the initialization, the program runs in a loop, incrementing time by 1/600 second and calculating outputs corresponding to this time. This high data rate is used only for integrating the dynamics associated with the sight and turret, and for updating of the true states (position, velocity, acceleration) of the target and helicopter. In addition, there is a 10 hertz data rate for updating the laser range measurement, and a 30 hertz rate for the fire control equations. Note that the simulated laser measurement is rounded to ± 5 meters to correspond to the value of the least significant bit from the laser.

True State Calculations

The block marked True State Calculations controls the nature of the engagement dynamics, and has two options: straight line fly-by, and target breakaway. The straight line fly-by was used as a baseline for design evaluation, and computes the inertial positions of a constant velocity target and helicopter. The particular case used for evaluation simulated a 100 meters/second closing velocity with a peak LOS rate of 0.4 radians/second. The exact conditions used are tabulated in Table 1.

Table 1. FLY-BY INITIAL CONDITIONS

	Initial Position (Meters)			Velocity (Meters/second)		
	X	Y	Z	V _X	V _Y	V _Z

	X	Y	Z	V _X	V _Y	V _Z
Ownship	0	0	25	20	0	0
Target	1500	250	175	-80	0	0

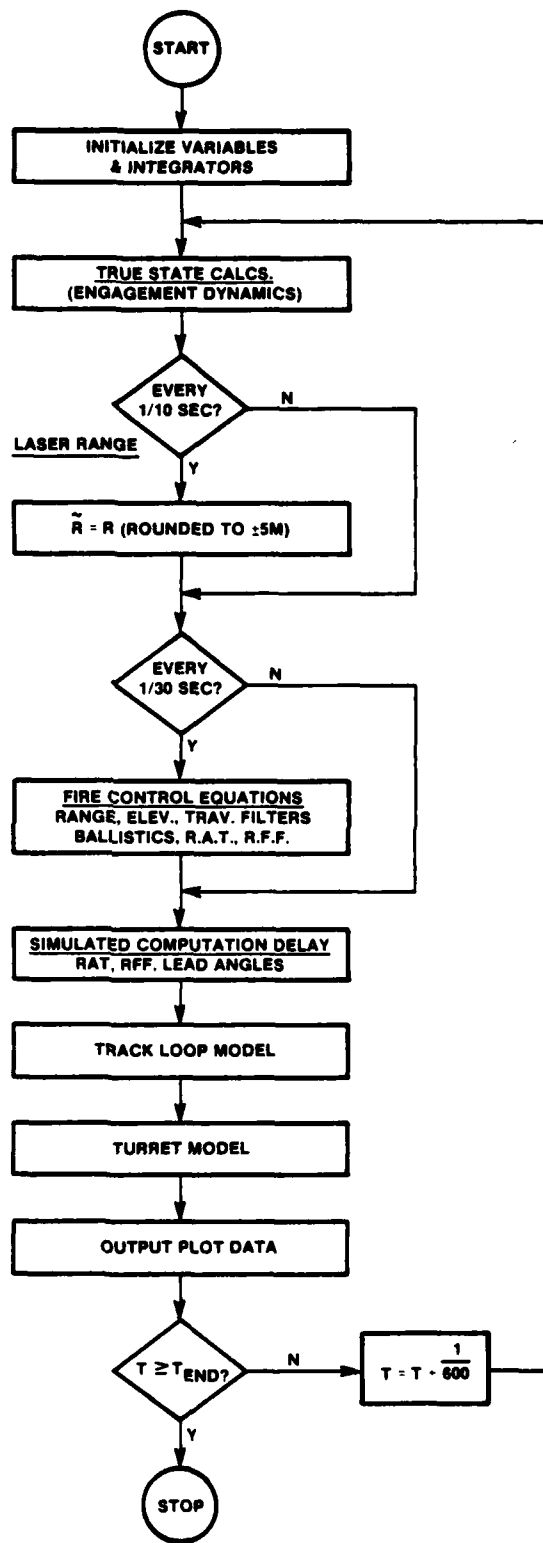


Figure 6. AIRSIM Flow Chart

Two other conditions were requested by the Army to be simulated: a collision course run, and a target breakaway. Both started from the initial conditions given in Table 2.

Table 2. COLLISION COURSE AND BREAKAWAY CONDITIONS

	Initial Position (Meters)			Velocity (Meters/second)		
	X	Y	Z	V_X	V_Y	V_Z
Ownship	0	0	50	20	0	0
Target	1500	0	50	-80	0	0

The collision course simulation used the same constant velocity equations as the fly-by, with only the initial conditions changed as noted. The target breakaway simulated a coalitude, 2g target maneuver starting at a range of 600 meters ($t = 9$ seconds simulation time). The acceleration was faded in with a 0.5 second time constant to approximate the response capabilities of a target aircraft.

Track Loop Model

A relatively simple model of the interaction between the man, sight, target, and fire control computer is used to simulate the air-to-air track loop, as shown in Figure 7.

The man is modeled as a transfer function which observes the angular tracking errors in each axis, and provides an output rate command to the sight. This command is proportional to the position error by the constant K_G , which has the units of radians/sec/radian, and also is equal to the bandwidth of the track loop, since all other loop gains are unity. A value of three has been used for K_G . In addition, the man is modeled by a pure delay (magnitude 25 milliseconds) plus a linear time constant of 1/7.5 seconds.

The man's rate command is summed with the rate-aided track signal to form the total rate command to the sight. The sight rate response is modeled by a first order time constant (120 radians/second), followed by an integration to produce sight position.

The observed angular tracking errors are formed as ratios of the components of relative target position R_s , D_l , D_m as shown in Figure 7. This LOS position vector is calculated from the cartesian target and ownship's position vectors (which have been calculated by the "True State Calculations") by a rotation through the sight angles.

Turret Model

The turret response model used by AIRSIM is shown in Figure 8. It is complicated by the fact that the sight and lead angle interface is computed in terms of direction cosine vectors. The servo

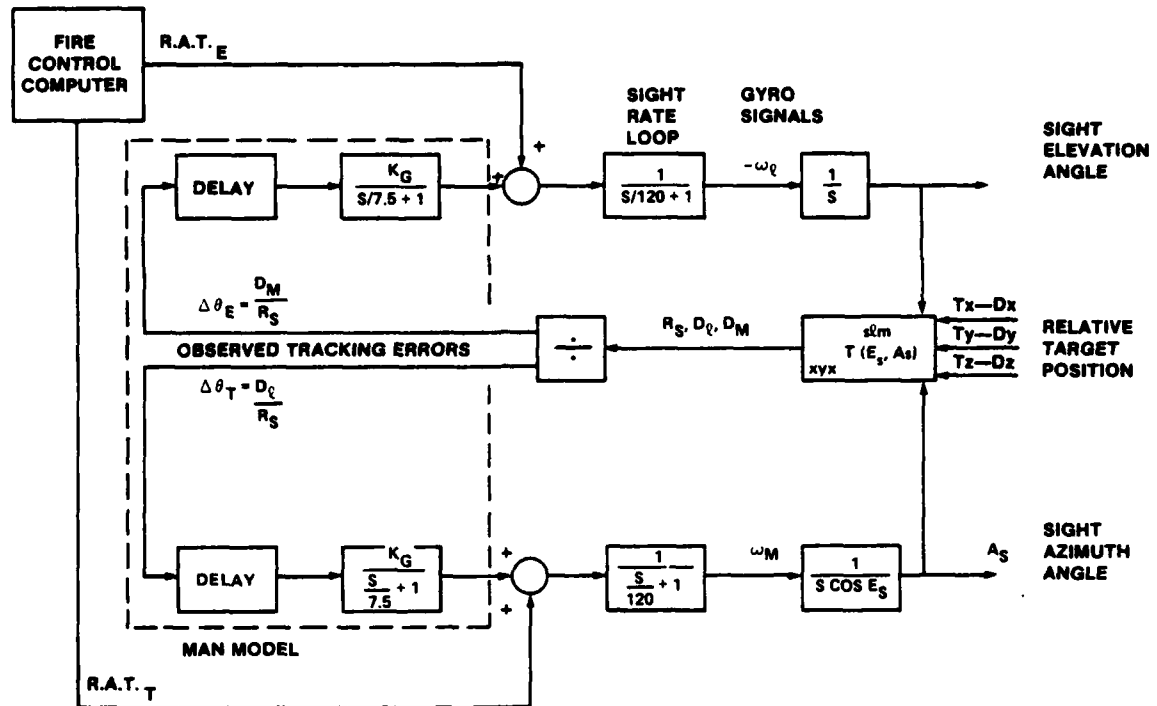


Figure 7. AIRSIM Track Loop Model

error equations simulate the turret resolver chain which separates the three component direction cosine commands into azimuth and elevation signals.

The rate loop model shows a low frequency integration together with a bandwidth of 120 radians/second. This was obtained by calculating a simplified expression for the turret closed rate loop from servo block diagrams. The rate feed forward commands are put through a low frequency differentiator in order to model the way that they are added in the track loop before the capacitor coupled tachometer feedback.

AIRSIM Data

Representative output plots from three AIRSIM runs are given in this section.

Figures 9 through 15 are from the target fly-by run described by the conditions in Table I. Target crossover, or the point of closest approach occurs just after $t = 15$ seconds. Note that the settling time of the computer is between three and five seconds, although the initial transient is small in this case because perfect track was assumed at time zero, when ACTION was pulled. Note also that only about $1\frac{1}{2}$ milliradians of peak tracking error are expected for this moderately fast target, and that this only occurs around crossover. After the initial transient there is an extended period of

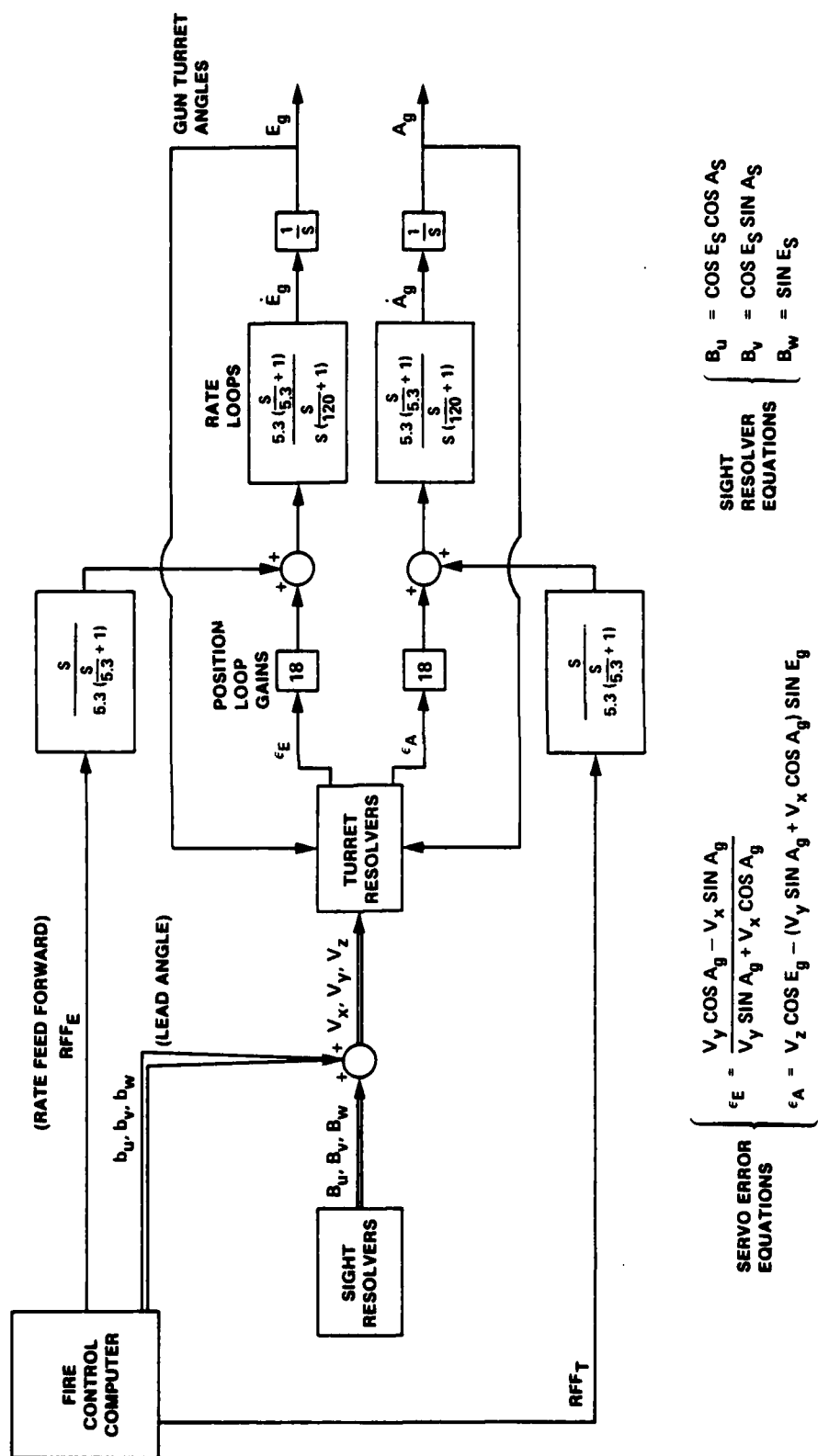


Figure 8. AIRSIM Turret Model

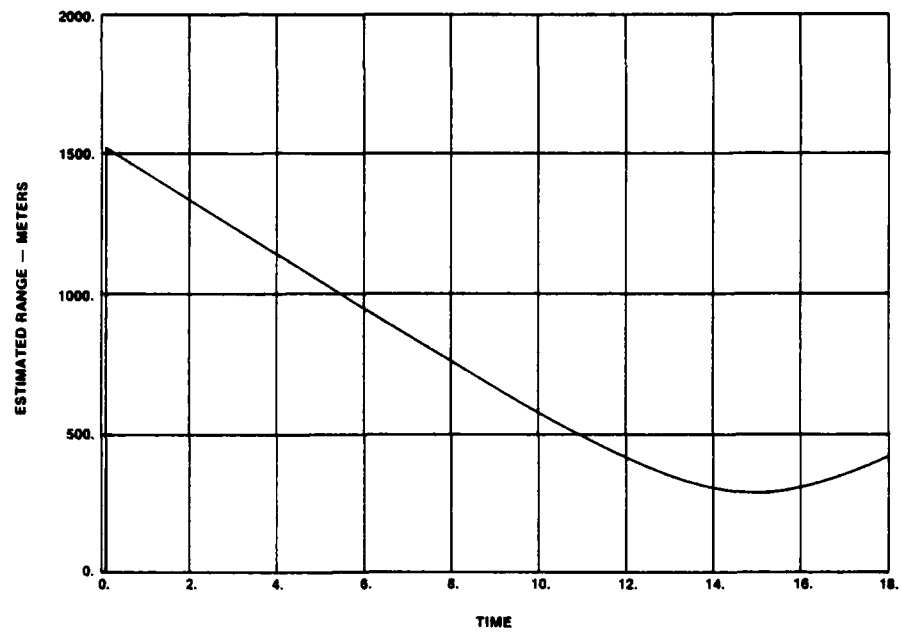


Figure 9. AIRSIM Data — Target Flyby

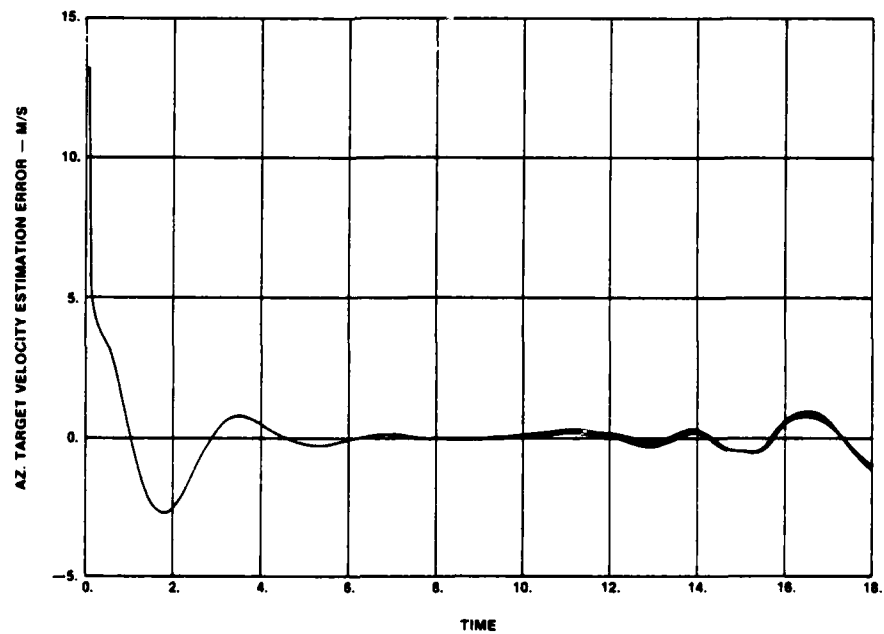


Figure 10. AIRSIM Data — Target Flyby

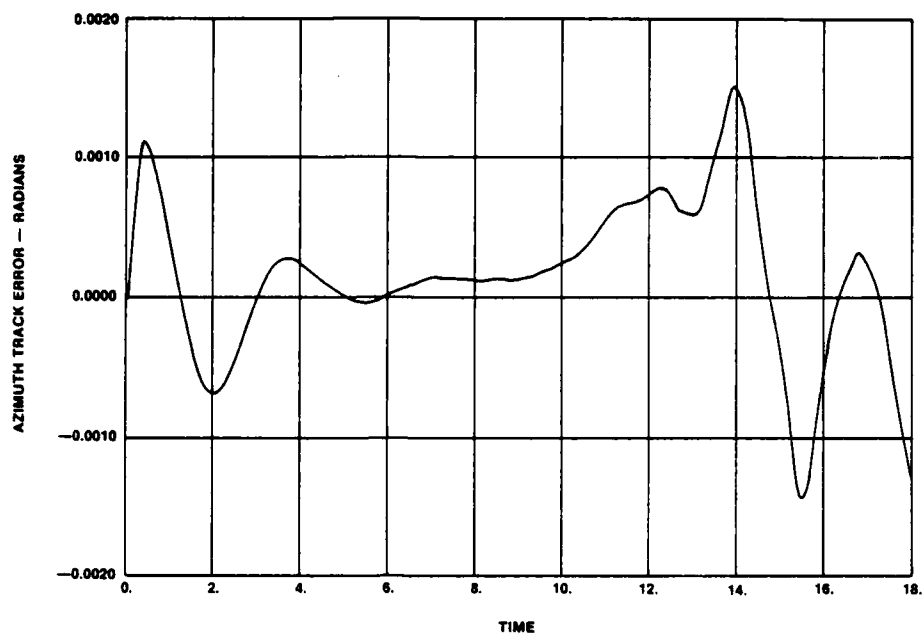


Figure 11. AIRSIM Data — Target Flyby

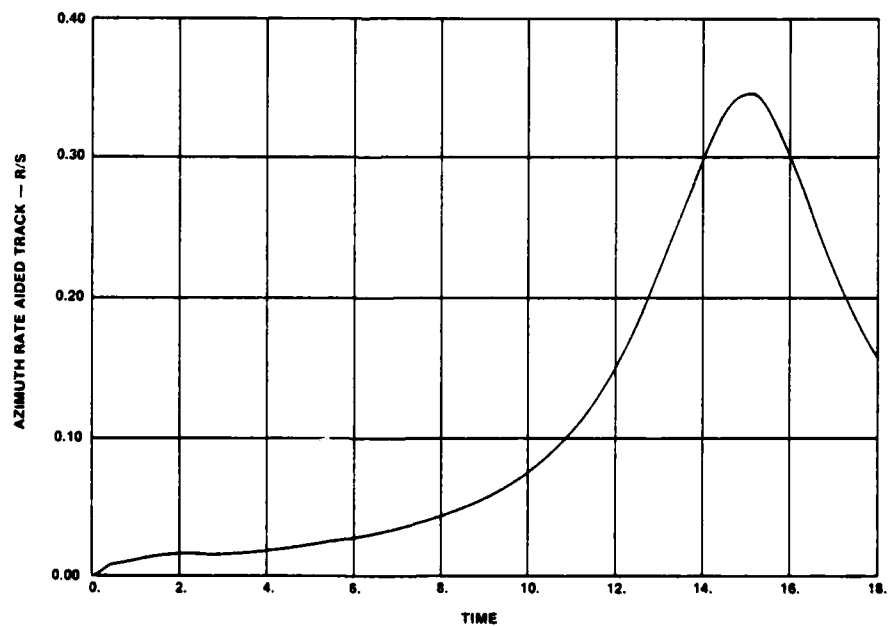


Figure 12. AIRSIM Data — Target Flyby

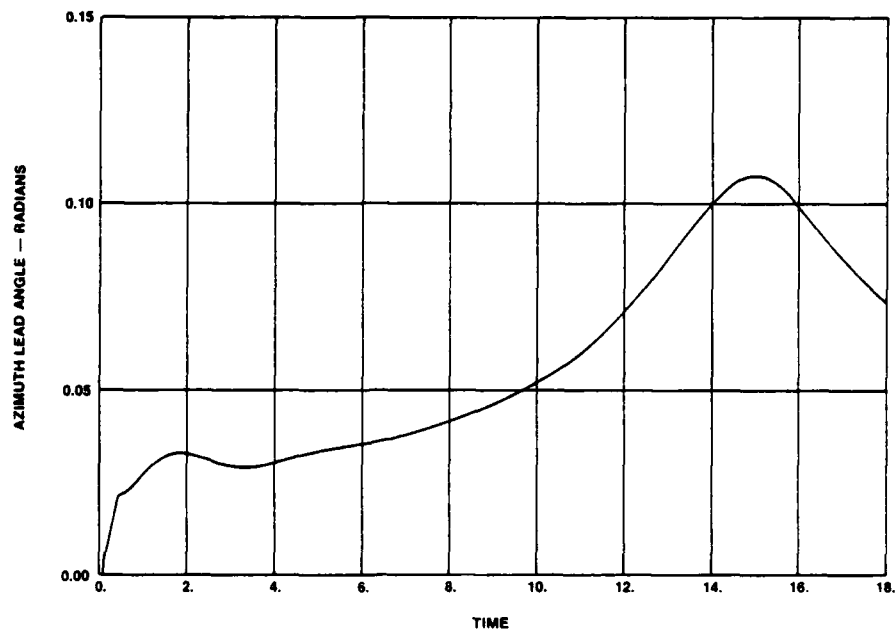


Figure 13. AIRSIM Data — Target Flyby

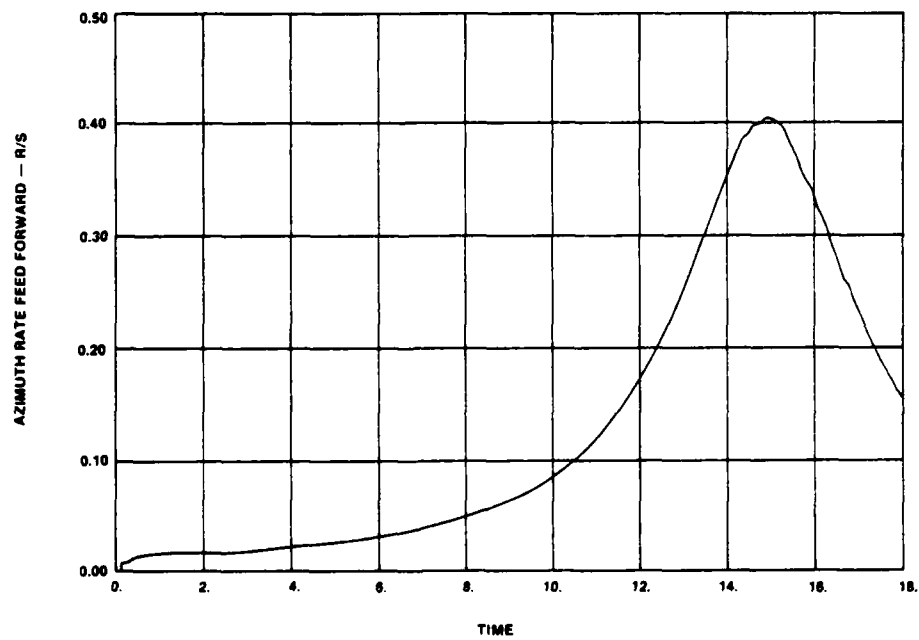


Figure 14. AIRSIM Data — Target Flyby

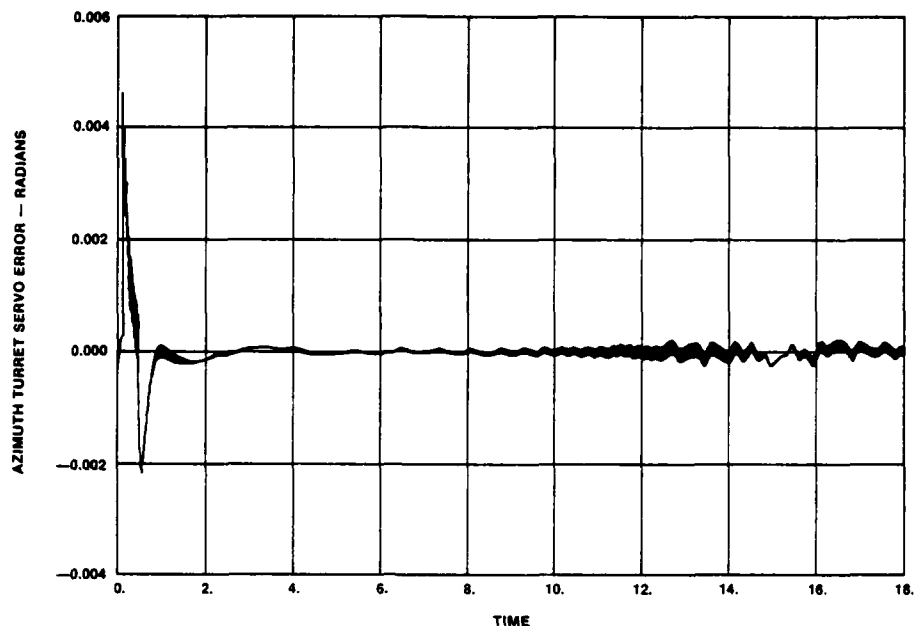


Figure 15. AIRSIM Data — Target Flyby

smooth, accurate track with ample opportunity for fire. Note that all computer outputs (rate-aided track, lead angle, and rate feed forward) are smooth, and the effects of the 0.4 second fade in (later changed to 0.8 second for the operational system) are readily seen. The turret servo errors are seen to be negligibly small, and consisting primarily of 30 hertz computer iteration noise.

Figures 16 through 19 are from the collision course run. After the initial transient, all of the variables in the azimuth and elevation channels (l and m) are zero — i.e., perfect track of this target is expected, so that all of the motion is in the range (\bar{s}) axis. The estimated acceleration curve is the most sensitive and since the true value is zero, is a measure of the filter error which is seen to be small, and approaching zero with time. Lead angle for this case is all superelevation; and from the gun elevation angle plot, seems to be fully settled well inside of two seconds.

Figures 20 through 28 are from the target breakaway simulation, as described in this section. For the first nine seconds, at which time the breakaway starts, the run is exactly the same as the collision course. The range at breakaway initiation is approximately 600 meters. At this time the velocity estimation error and tracking error increase quite dramatically due to the sudden change in acceleration, and $2\frac{1}{2}$ to 3 seconds is needed for the solution to resettle to the point where both the track and the estimated velocity are good.

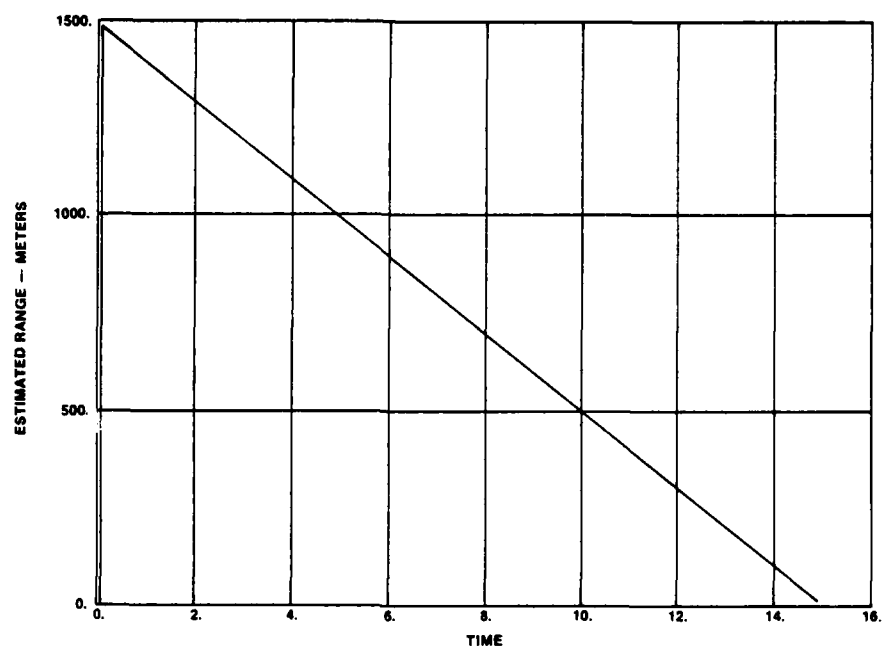


Figure 16. AIRSIM Data — Collision Course

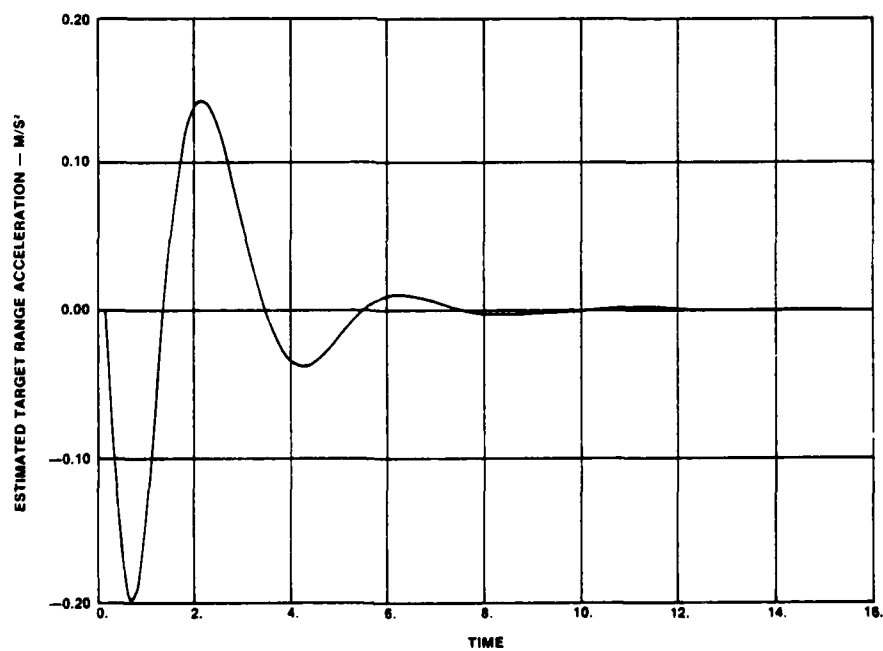


Figure 17. AIRSIM Data — Collision Course

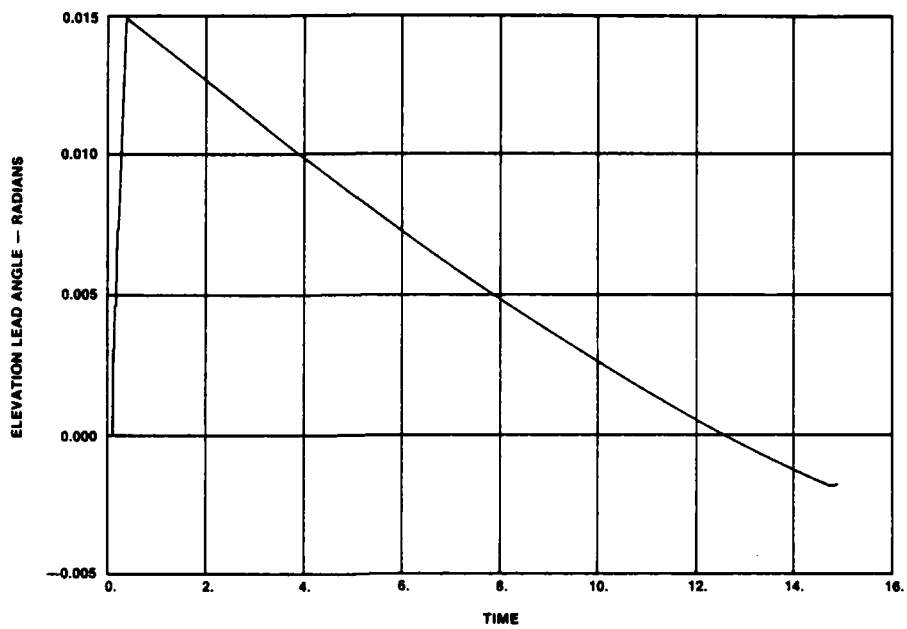


Figure 18. AIRSIM Data — Collision Course

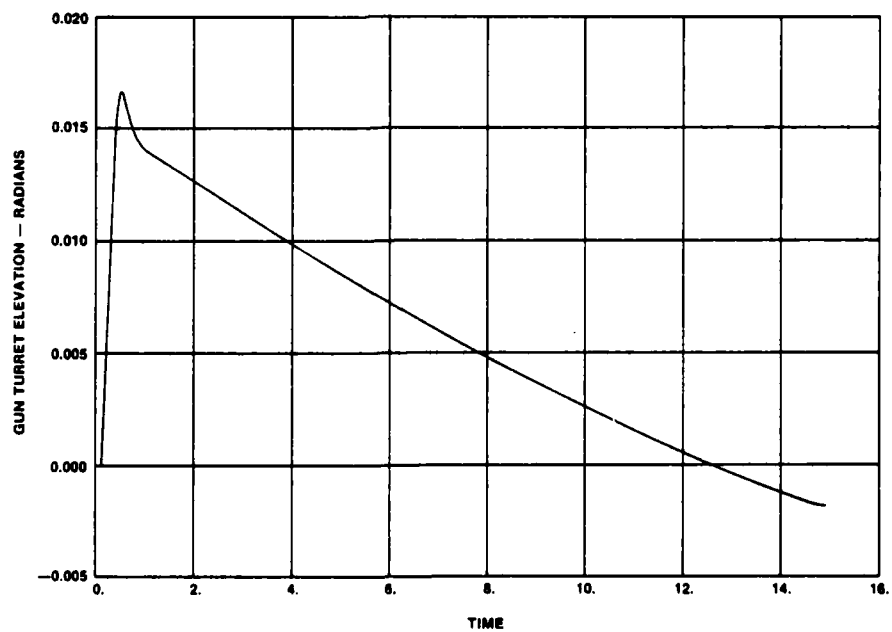


Figure 19. AIRSIM Data — Collision Course

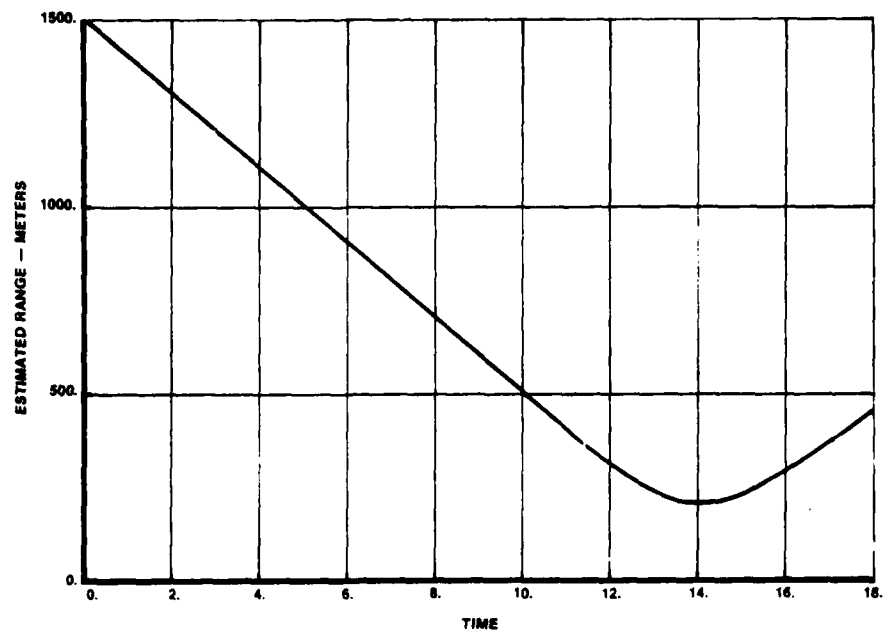


Figure 20. AIRSIM Data — Target Breakaway

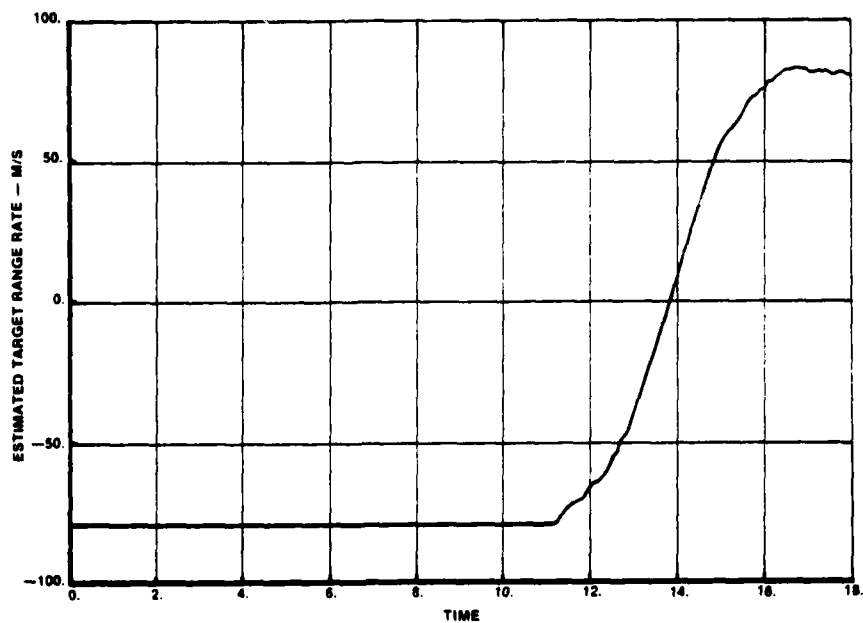


Figure 21. AIRSIM Data — Target Breakaway

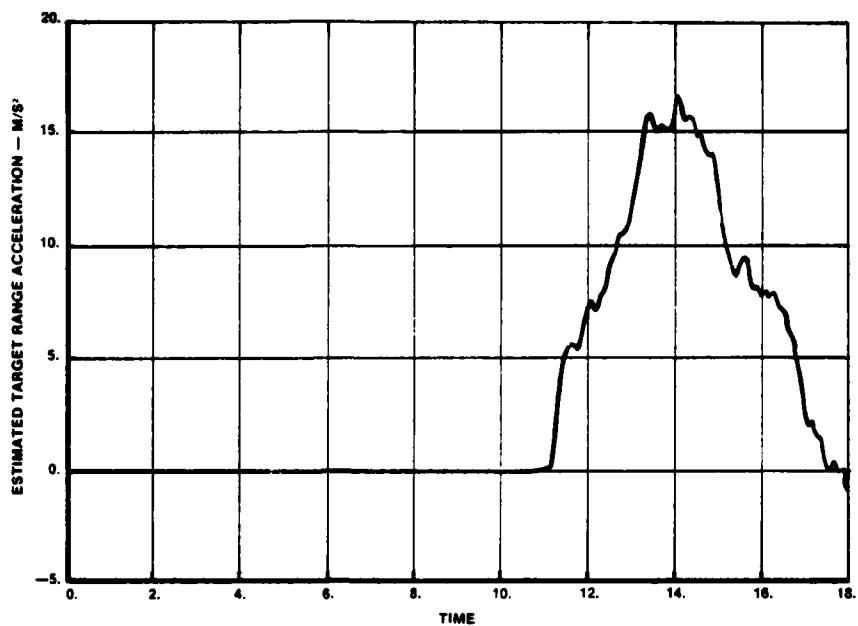


Figure 22. AIRSIM Data — Target Breakaway

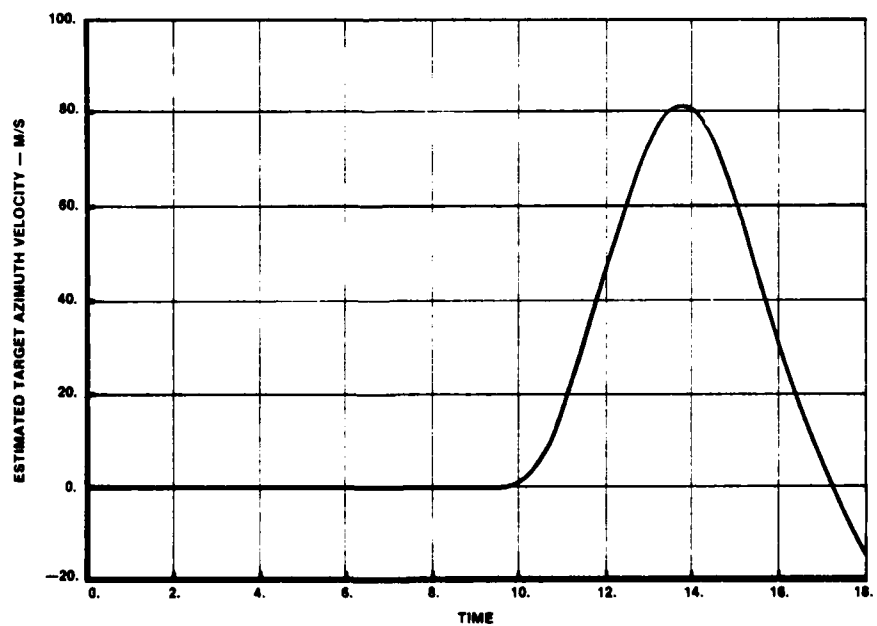


Figure 23. AIRSIM Data — Target Breakaway

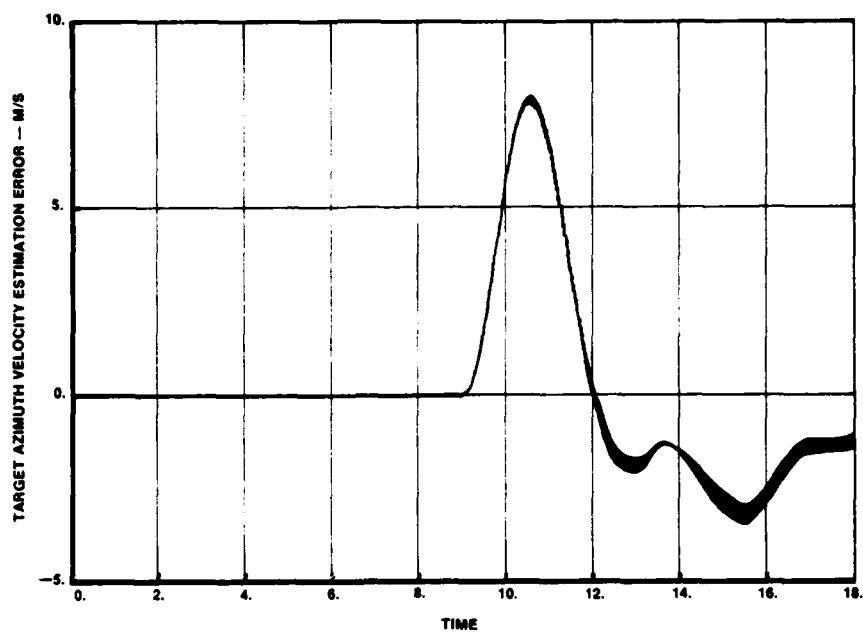


Figure 24. AIRSIM Data — Target Breakaway

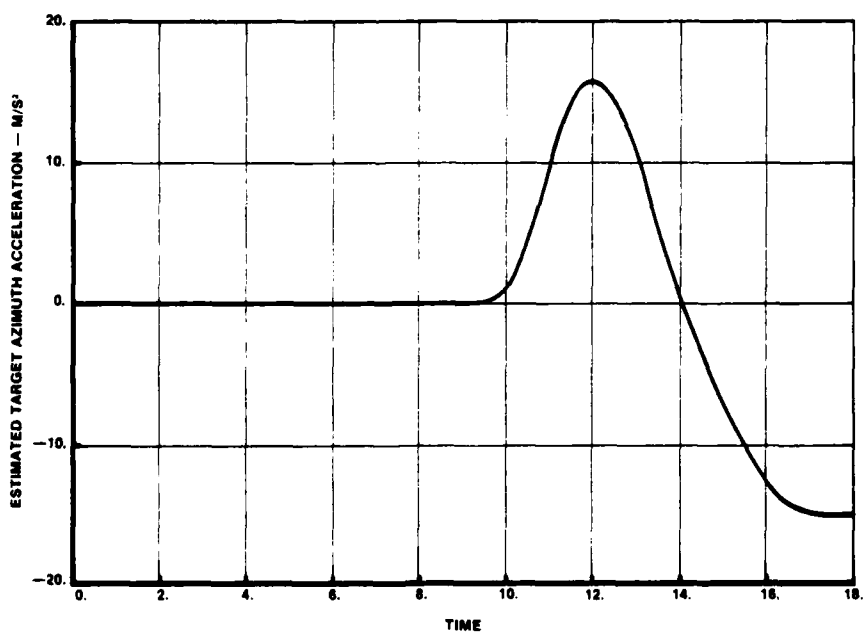


Figure 25. AIRSIM Data — Target Breakaway

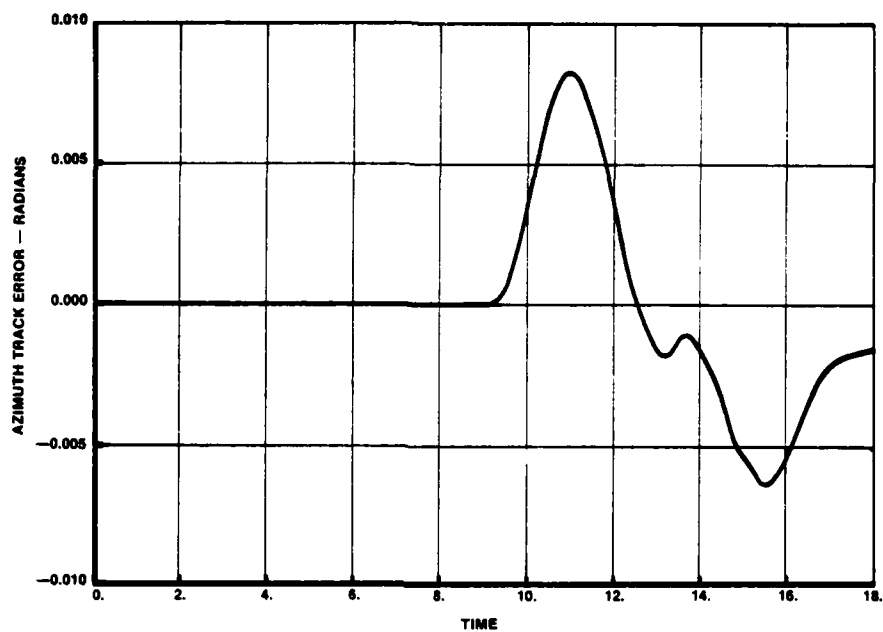


Figure 26. AIRSIM Data — Target Breakaway

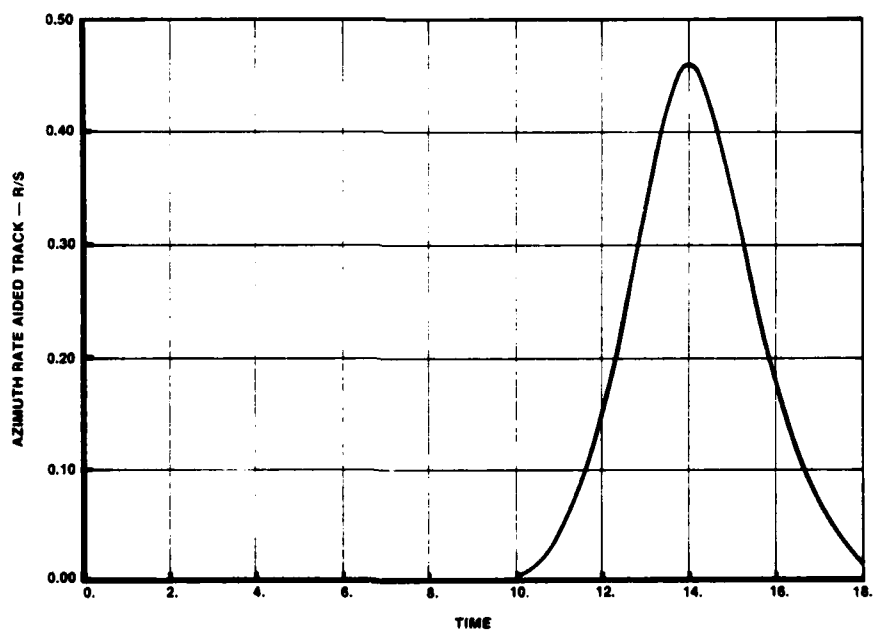


Figure 27. AIRSIM Data — Target Breakaway

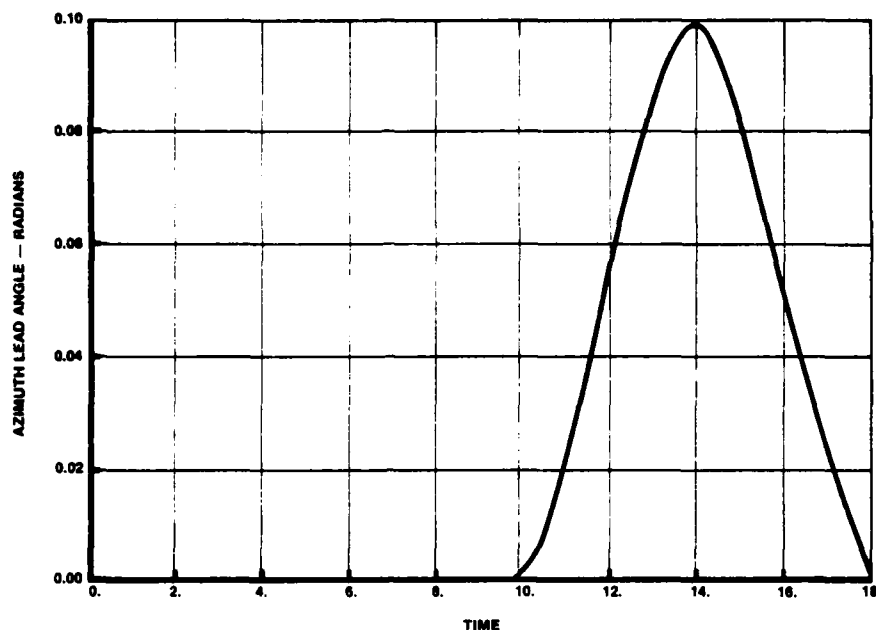


Figure 28. AIRSIM Data — Target Breakaway

TARGET MOTION AND TACTICS

The following scenario has been hypothesized by the General Electric Company, Armament Systems Department.

The primary mission of the U.S. Army's attack helicopters is to engage and destroy the armor of opposing forces. This mission will be accomplished from very low altitude, primarily with the use of guided antitank missiles. The Soviet's attack helicopters have the same primary mission but another mission is quite conceivable. This is the protection of their armored forces from the efforts of U.S. attack helicopters.

In this scenario, the U.S. helicopter (blue) would initially be at hover, at low altitude, and possibly engaged with missile attack on advancing armor. The Soviet helicopter (red) would be vectored to the general area of the U.S. aircraft. They would initially be at a higher altitude and would be flying at nearly their maximum velocity. Upon sighting the blue helicopter the red helicopters would press their attack radially in a shallow dive. The red helicopter could be expected to use any of its armament which includes guided antitank missiles, rockets and high rate-of-fire cannon. The red helicopter would press its attack until it killed its target or until the pilot felt that his depth of penetration of the FEBA had become untenable. At that time the red helicopter would turn away and the attack would be taken up by following helicopters. During the turn the red helicopter would attempt to avoid presenting a broadside to the blue helicopter.

The blue helicopter, which would probably be screened from the view of the red helicopter by foliage or terrain, should detect the presence of the red helicopter before it is in turn detected. It would remain at hover and hidden as long as possible. If brought under attack, it would hopefully be aided by air defense weapons in the vicinity (Redeye, Stinger, VADS, or DIVADS). If not, it would be required to defend itself. At short ranges of encounter (1500 meters or less) its defensive weapon would probably be the turreted, high rate-of-fire cannon.

The blue helicopter may maneuver to avoid fire but it would try to present a frontal area to the attacker both to minimize the area it presents to the red aircraft and to keep the attacker within its field of fire. The maneuver would probably be lateral motion.

A diagram of the encounter is shown in Figure 29 with probable aircraft velocities, engagement ranges and altitudes shown.

One other scenario, besides chance encounters, is possible but much less likely. Soviet helicopters have an airmobile mission to deliver and cover assault forces. It is conceivable that U.S. helicopters would be called upon to intercept this operation. The Soviets would, most likely, attempt to use superior speed to bypass the intercepting blue helicopters. In that event, the flight paths of the red helicopters would be low altitude, high velocity and crossing — a typical air defense problem. The altitudes would be less than 100 meters, with velocities approaching 180 knots and at crossing ranges of 500 to 2000 meters. Of the present armament aboard U.S. attack helicopters, the cannon would be the most likely used weapon of attack.

FIRING RATE ANALYSIS

The question of the "optimal" rate-of-fire for helicopter gun armament systems has long been discussed. Most agree that as more rounds are fired at a target, the probability of hitting and killing it is increased. This implies, given a specific time, length of burst, that the fire rate should be as high as can be achieved with the machinery in use. This thesis is sometimes countered with the argument that, given a specific number of rounds to be fired at the target, it is better to fire slowly and to correct the aim between each shot. Other arguments are concerned with the tradeoff between fire control accuracy and gun fire rate. Regardless, all arguments are reduced to acceptance of the fact that the more rounds fired, the greater the hit probability and to the question of whether it is better to fire them slowly or quickly.

Arguments, as discussed above, frequently fail to take into account the constraints that are basic to the choice of the best fire rate. For instance, neither an unlimited time to fire at the target nor an unlimited amount of ready ammunition will be available. The former will be limited by the tactics of aerial gunnery and the latter by weight limitations imposed by the aircraft design. In addition, the aircraft will most likely be required to be prepared to engage more than one target per mission and such parameters as target range (which could effect the choice of fire rate) cannot be predicted in advance.

A method that can be used to estimate the "best" fire rate is to maximize some function such as the expected number of targets killed (or hit) per mission in the presence of such constraints as the

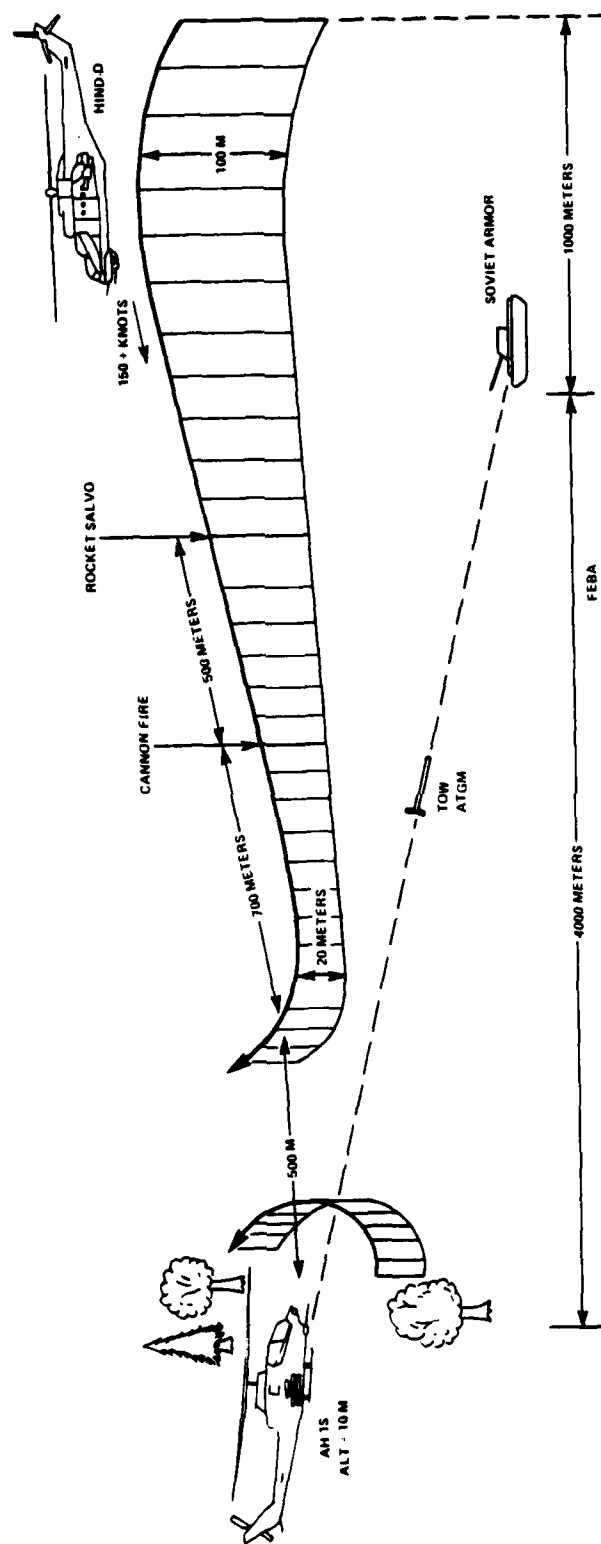


Figure 29. FEBA Air-to-Air Engagement Scenario

total number of ready rounds available. This method has been applied to the analysis of the rate-of-fire for the M197 gun armament system that is mounted on the AH-1S attack helicopter. The cannon is a 3-barrel 20-mm Gatling type and the ready ammunition supply is 750 rounds. This maximization was done with a Monte Carlo process.

The scenario chosen for the analysis was air-to-air combat between the AH-1S and a hostile helicopter. Target kill (an A-kill criteria was used) was defined as at least one hit in the target's vulnerable area. The value function that was maximized was the expected number of targets killed during a mission.

The factors of the engagement during a mission cannot be predicted beforehand, but they can be described statistically. This was done in the Monte Carlo analysis by the inclusion of probability distribution¹ functions. These functions were derived from data of cannon firings from the J-CATCH II and J-CATCH IV tests². The probability distribution functions were of the burst length in seconds, the firing range in meters and the number of targets engaged per mission. An estimated frontal vulnerable area was used. Aspect angle of the target could have been included as a distribution function, but data in this form was not available at the time of the analysis. Only one burst per target was assumed at the suggestion of D. O'Neill though the number of bursts per target could also have been included as a distribution function. The distribution functions used in the analysis are shown on Figures 30, 31, and 32.

Kill probabilities were calculated with the use of an "independence" model where the aim error shot-to-shot was assumed to be uncorrelated. The gun pointing error was assumed to be a linear function of the projectile time-of-flight to the impact range with the target. This equation was an attempt to account for the fire control errors which are at least a linear function of range. The error equation which was used is given by $\sigma_A = (2 + 8 T_F)$ milliradians, where σ_A is the radial standard deviation of the aim error and T_F is the projectile time-of-flight. This was a conservative estimate of the error statistics that could be encountered during air-to-air combat. Hopefully, this estimate can be updated with the MIDI data from the Ft. Bliss firing tests.

¹ A probability distribution function $F_Y(y)$ is defined as:

$$F_Y(y) = P[Y \leq y]$$

² Communication from D. O'Neill, AMSAA, to J. Wagner, General Electric Company, August, 1979.

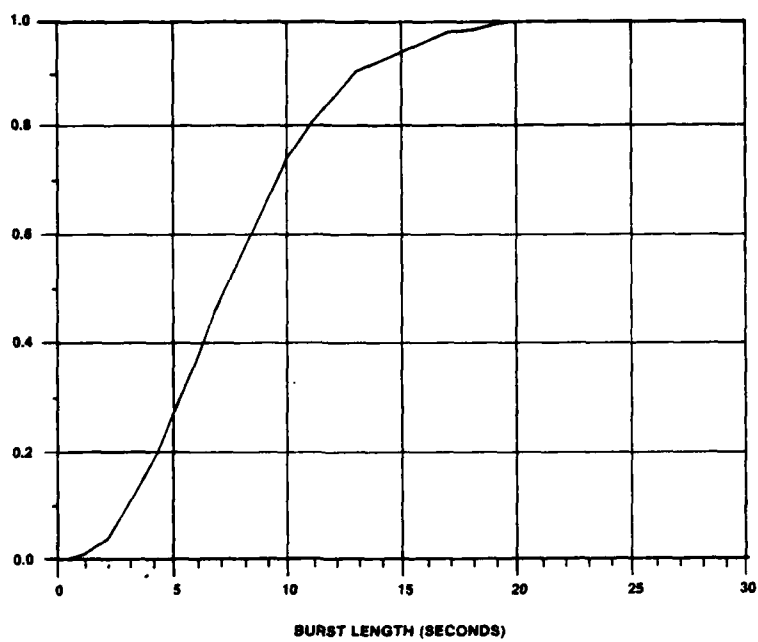


Figure 30. Probability Distribution Function

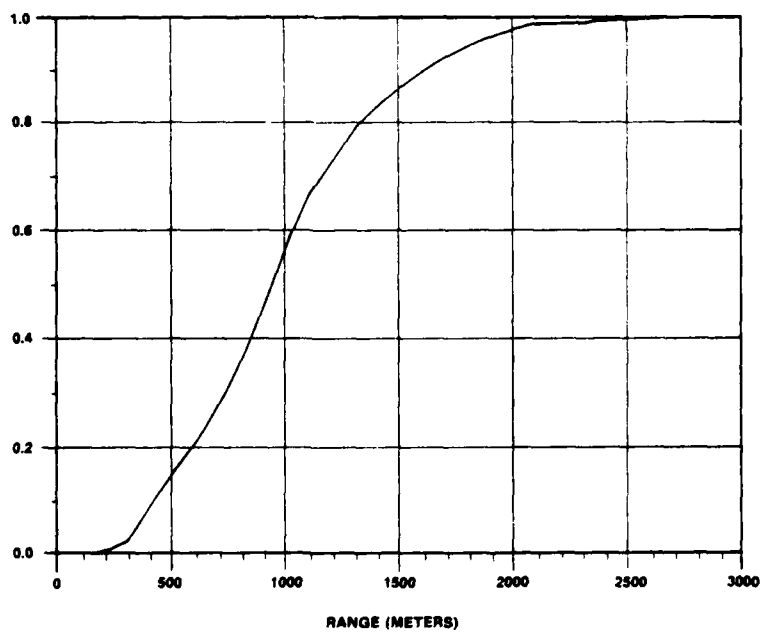


Figure 31. Probability Distribution Function

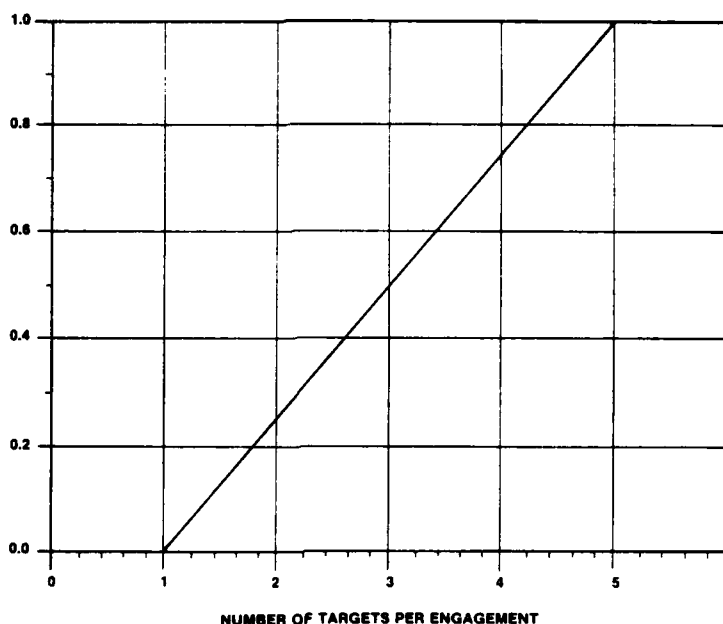


Figure 32. Probability Distribution Function

Figure 33 shows a summary of the results of the analysis. It is a plot of the expected number of targets killed per mission (ENKM) versus the cannon rate-of-fire in rounds-per-minute. This shows ENKM to steadily increase as fire rate is increased until a fire rate of 1500 shots-per-minute is reached, after which ENKM decreases. Also shown on the chart is the probability that the aircraft will deplete its ammunition supply before the mission is completed (PEXHM). This probability is essentially zero until a fire rate of 900 shots-per-minute is reached. After 1500 shots-per-minute the probability of running out of ammunition during a mission is 20 percent.

For a check on the sensitivity of the calculation of the "best" fire rate, two additional cases were examined. The first was with the vulnerable area increased by a factor of five as an estimate of the side vulnerable area, and the second with the gun pointing error equation reduced to $\sigma_A = (2 + 4 T_F)$. For both cases the "best" fire rate was in excess of 1000 shots-per-minute. The expected number of kills per mission was increased. The results of analyses are shown on Figures 34 and 35.

Based on this analysis, a fire rate of 1500 shots-per-minute appears to be "best," as it maximizes the kill probability with an acceptably low probability of exhausting the ammunition supply.

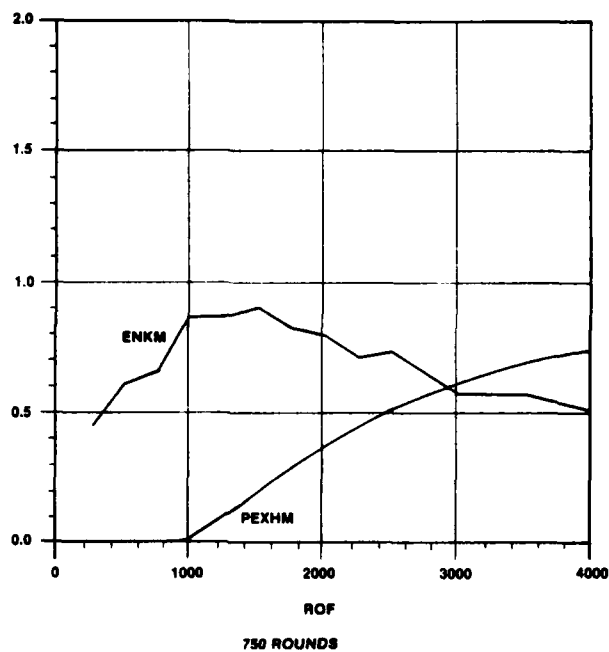


Figure 33. Expected Kills Per Mission (ENKM) and Probability of Exhausting Ammunition (PEXHM) Versus Fire Rate

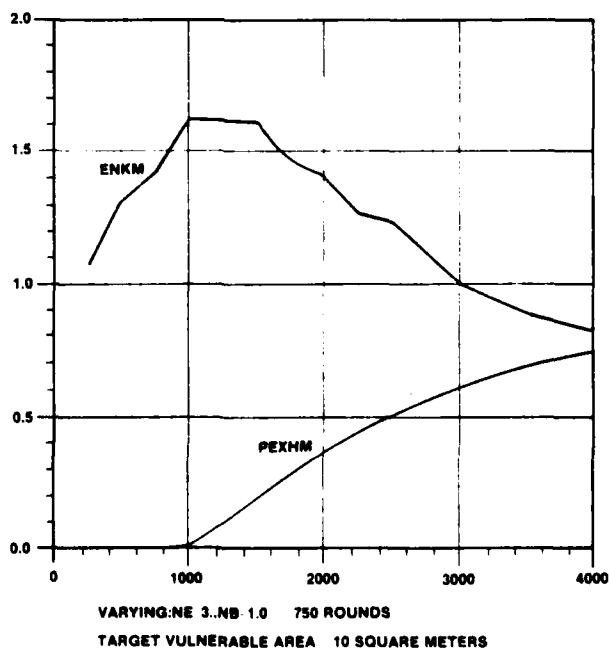


Figure 34. Expected Kill Per Mission (ENKM) and Probability of Exhausting Ammunition (PEXHM) Versus Fire Rate

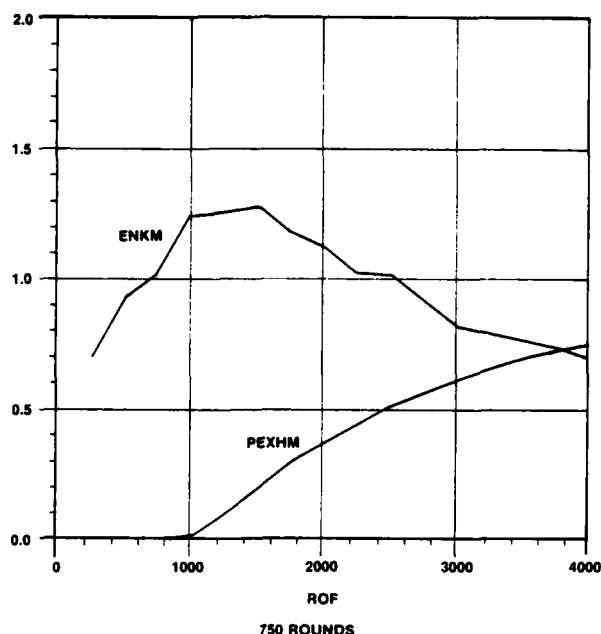


Figure 35. Expected Kill Per Mission (ENKM) and Probability of Exhausting Ammunition (PEXHM) Versus Fire Rate

SENSOR AND HARDWARE REQUIREMENTS

In order to provide an effective air-to-air gunnery capability in the MWFCs aircraft, additional instrumentation is required as documented here. Changes in the gun and turret system are described later in this section.

The MWFCs computer is one of a kind, hard-wired, and non-software programmable. It is not representative of current computer technology and therefore not a good choice for an air-to-air fire control demonstration. A more adequate fire control computer, together with an accurate Aircraft State Estimator (ASE) already programmed in it, is available from the Closed Loop Fire Control System. In order to save development time, this computer and software was chosen to be used in the MWFCs aircraft.

The Inertial Measurement Unit from the CLFCS must also be added because the CLFCS ASE requires this sensor package which includes three body gyros and three accelerometers. It should be noted that it is very unlikely that such an IMU (or at least the gyros from it) would be needed if an operational air-to-air system were to be designed. The IMU gyros were used on this test bed development simply to be able to use existing software, and minimize development time.

The MWFCs laser ranger was used, again for ease in developing a test bed, but the beamwidth is extremely narrow ($\frac{1}{2}$ milliradian) for this application. A beamwidth of 2 to 3 milliradians would be better for engaging aerial targets. When ranging a ground target, a very small error is made if the beam misses the target and hits the ground instead. However, if the beam misses an aerial target, it

will most probably hit nothing else within the range gate, and thus will be completely lost. This is especially critical when acquiring a high rate target, and attempting to lock on with rate-aided track. A wider beam eases the accuracy of manual track that is required before the transition can be made, and assures the computer of receiving more returns during this critical period so that a smooth, rapid transition can be made.

TURRET AND GUN CHARACTERISTICS

A simplified block diagram of the AH-1S turret servos is given in Figure 36. An error analysis can be performed from this block diagram by first obtaining the corresponding open loop frequency response for the position loop

$$GH = \frac{95.4 \left(\frac{S}{5.3} + 1 \right)}{S (S + .02) \left(\frac{S}{120} + 1 \right) \left(\frac{S}{140} + 1 \right)}$$

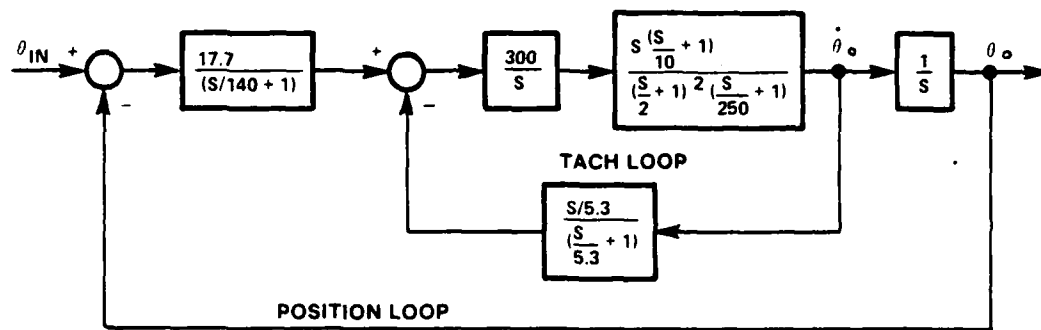


Figure 36. Turret Servo Block Diagram

Base Motion Errors

In order to size the magnitude of turret servo pointing error due to ownship's motion, this motion is broken into two parts.

- Low frequency motion resulting from evasive maneuvers or air turbulence is modeled by

$$\dot{\theta} = 0.5 \sin 1.57t \text{ radians sec.}$$

- High frequency motion resulting from rotor induced vibration is modeled by

$$\dot{\theta} = .05 \sin 70t + .05 \sin 35t \text{ radians sec.}$$

The resulting angular amplitude is found by integrating with the result

$$\theta = .32 \cos 1.57t + .0014 \cos 35t + .0007 \cos 70t \text{ radians}$$

The resulting position error is found by dividing each component by the magnitude of $(1+GH)$ at that frequency

$$\epsilon = 8.1 \cos 1.57t + .9 \cos 35t + .6 \cos 70t \text{ milliradians}$$

Thus, we see the peak dynamic errors due to base motion are expected to be on the order of 9 milliradians. An order of magnitude improvement of these errors can be obtained by adding three spring restrained gyros to the turret to sense and compensate for this motion through the high bandwidth rate loop. This type of gyro stabilization is recommended to minimize these types of gun pointing errors.

Target Motion Errors

When tracking a high angular rate target there is a turret servo following error proportional to the angular acceleration. This turret servo has an acceleration constant of 95.4 (the open loop gain at 1 radian/second) which is the proportionality constant between acceleration and resulting error. To size the magnitude of this error, we will assume a 1 radian/second crossing target, which can be shown to have a peak angular acceleration of .65 radians/second². Dividing this acceleration by the servo acceleration constant shows that the peak servo following error can be expected to be about 7 milliradians for this condition.

The addition of turret rate commands from the fire control computer, known as rate feed forward, in addition to the position command can reduce these peak errors by an order of magnitude. Addition of rate feed forward turret commands are therefore recommended.

Gun Firing Rate

As shown by the analysis of the firing rate, a rate-of-fire significantly higher than the standard 750 shots-per-minute is needed to maximize target kill probability. Doubling the rate to 1500 is a convenient choice that is close to the "best" rate and is therefore recommended.

AH-1S MODERNIZED COBRA RECOMMENDATIONS

In order to provide the AH-1S Modernized Cobra with an effective air-to-air fire control capability, changes are needed in the sensor set, fire control computer inputs and outputs, and computer software. The following recommendations are based on available information of the AH-1S fire control, and may not be up to date.

Sensors

The following additions and improvements to the fire control sensors are listed in order of priority.

- Add a roll rate gyro (of rate-integrating quality) to the line of sight axis of the TOW sight. This input is necessary for implementation of accurate, LOS based fire control equations.

- Add "hull rate" gyros to the gun turret to augment stabilization of the gun line during ownship's maneuvers. Spring restrained gyros are adequate for this purpose.
- Increase the laser beamwidth to 2 or 3 milliradians (half power point). A range of 2500 is the maximum needed for air-to-air gunnery, however, the power must be put in a much wider beam than the $\frac{1}{2}$ milliradians used on the MWFCs.
- Increase the pulse repetition rate of the laser rangefinder from the present value of three to four pulses per second, which is marginal for air-to-air. A value of 10 pps is fully adequate.

Computer Inputs and Outputs

In order to accurately track the relatively high speed target and ensure that the gun turret accurately follows the command, four signals must be generated by the fire control computer and output to the TOW sight and gun turret. These signals are:

- Rate-Aided Track (RAT) signals, one each in elevation and traverse, should be sent to the TOW sight. These signals should include compensation for target as well as ownship's motion. They allow accurate track of a much higher angular rate target than can be done manually. RAT permits the gunner to operate in the low gain, low force region of the thumb button where he can make small, accurate corrections to the large rates generated by RAT.
- Rate Feed Forward (RFF) signals to the azimuth and elevation gun turret servo rate summing junctions are very helpful in reducing dynamic gun pointing errors. These errors can be reduced by an order of magnitude by RFF signals for a high rate target.

Additional fire control computer inputs to perform the air-to-air fire control task will include the following:

- A line-of-sight roll gyro as discussed above.
- The gunner hand control track signals will have to be added if the filter implementation is the same as used for this contract.

Fire Control Computer Software

Rather extensive changes will be required to the fire control software in order to incorporate an air-to-air gunnery capability. These changes include the following:

- The target state estimator will probably have to be completely reprogrammed in order to explicitly account for target motion. It is recommended that a constant or nearly constant acceleration model be used.

- The ballistics computations must also be changed to include the effects of target motion during the projectile time-of-flight. A constant velocity predictor is recommended.
- The generation of rate-aided tracking signals for the sight, and rate feed forward signals for the turret should be added.
- Laser range coasting logic should be added if not already available.
- The executive program will have to be modified or rewritten to handle the new routines and increased input/output.

SECTION 4

AIR-TO-AIR FIRE CONTROL SOFTWARE

OVERVIEW

The air-to-air software has been written in assembly language for the CDC 469-8k minicomputer. The assemblies have been done on ARRADCOM computers, CDC 6000 via Intercom timeshare system. The latest source has been saved on magnetic tape reel #8468, dated October 19, 1979 at ARRADCOM. The loadable program has been punched on paper tape to be forwarded to ARRADCOM. CDC 469-8k memory has been loaded with the latest version of the program using General Electric memory loader.

ORGANIZATION

The real time software in CDC 469 computer consists of the following sections:

- Page zero variables/constants
- Executive
- Input scaling routine
- Laser-read, scale and range gate
- Hand control filter
- Two stage scaling routine for hand control inputs
- Aircraft state estimator
- Fire control system
- Output routines
- Interrupt service routine
- Flight recorder subroutine
- Arithmetic routines
- General Electric memory loader
- Variables and constants
- Test patch to plot and display

Table 3 shows the current memory map of the CDC 469.

EXECUTIVE

The executive controls all logic and timing functions, subroutine calls and input/output operations. The timing is based on a real time clock (30 Hz) to which the executive synchronizes at power on.

The longest path through the software has been measured to be 30 milliseconds out of a total available time of 33.33 milliseconds.

Table 3. MEMORY MAP

SECTION DESCRIPTION	IDENTIFIER	ADDRESS
Page Zero	PAGEO	000000 - 000377
Executive	(EXEC)	010407
	COLD	010407
	START	010442 - 010517
	WAITLOP	012544 - 012604
A/C State Estimator	A/C Estimator	011015 - 011630
Input Scaling	PRECOMP	013000 - 013171
Laser	LASER	012000 - 012077
Initialization	INITO	015235 - 015306
	INITI	014600 - 014734
	FIRINTT	015307 - 015340
Hand Control Filter	OMEGA	012200 - 012241
Two Level Gain	DGAIN	016500 - 016613
Output	OUTPUT	012400 - 012536
	OUT2	012700 - 012751
Interrupt Service Routine	INTR	015060 - 015160
Flight Recorder	FREC	014500 - 014574
Arithmetic	LSQRT	014750 - 015022
Subroutines	RSHIFT	015161 - 015163
	LSHIFT	015164 - 015166
	MATM	015167 - 015234
	SIN	013440 - 013454
	COS	013455 - 013460
	ATAN	013400 - 013437
Memory Loader	GELOAD	013500 - 013563
Variables	—	000400 - 003700
Test Patch	—	013300 - 013315
Fire Control System	FIRECTL	004000
	INPUT	004000 - 004266
	RNCOAST	004400 - 004554
	INIT73	004600 - 004661
	FILTRS	004750 - 007065
	TFLT	007100 - 007321

The discrettes are read, unpacked and packed, and the A D channels are initiated by the executive.

At the conclusion of one cycle through the software, the system waits in a loop until 30 Hz interrupt arrives. See Figures 37 and 38 for a more detailed description of the executive routine. Each of the subroutines called by the executive are described separately.

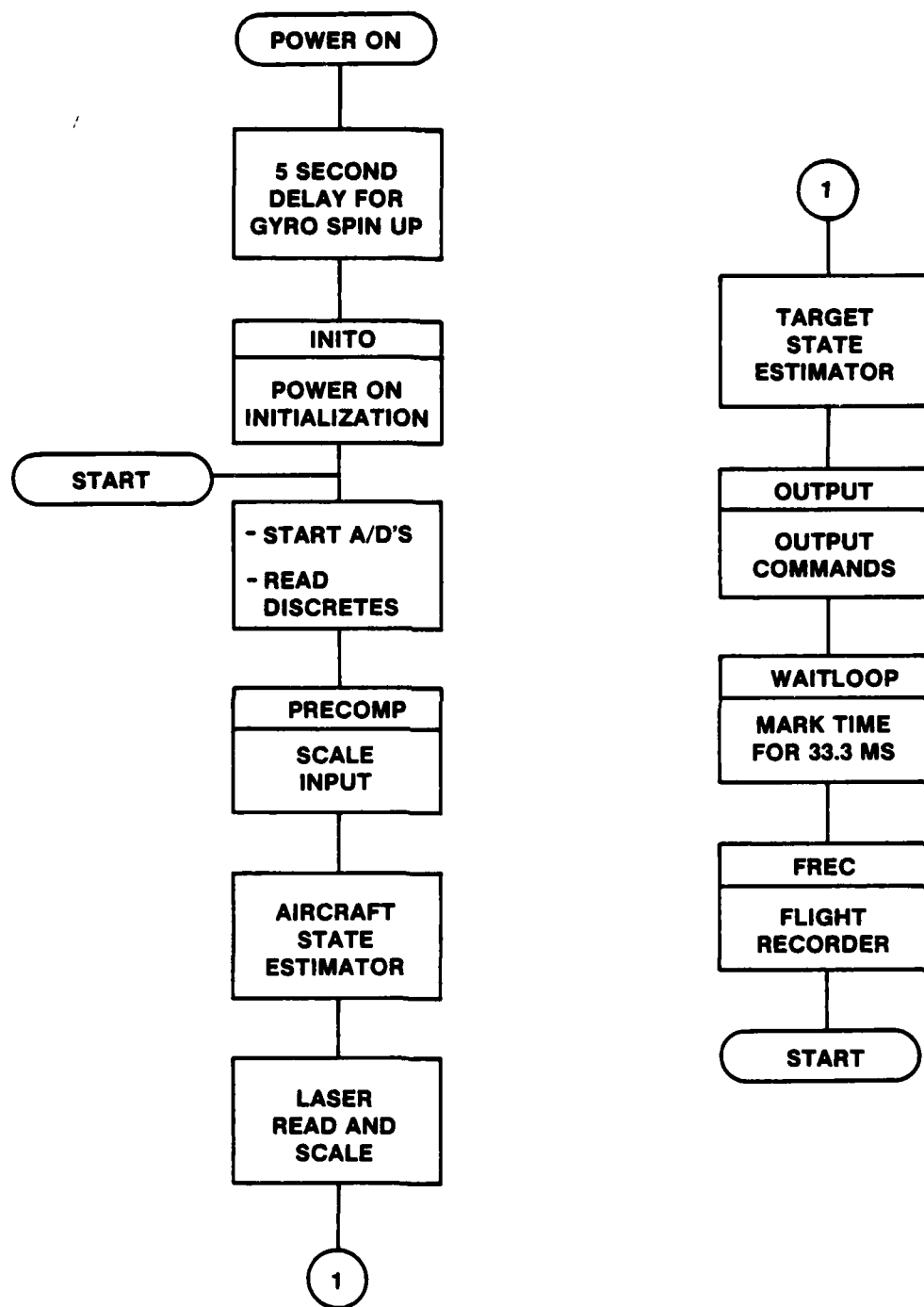


Figure 37. Top Level Flow

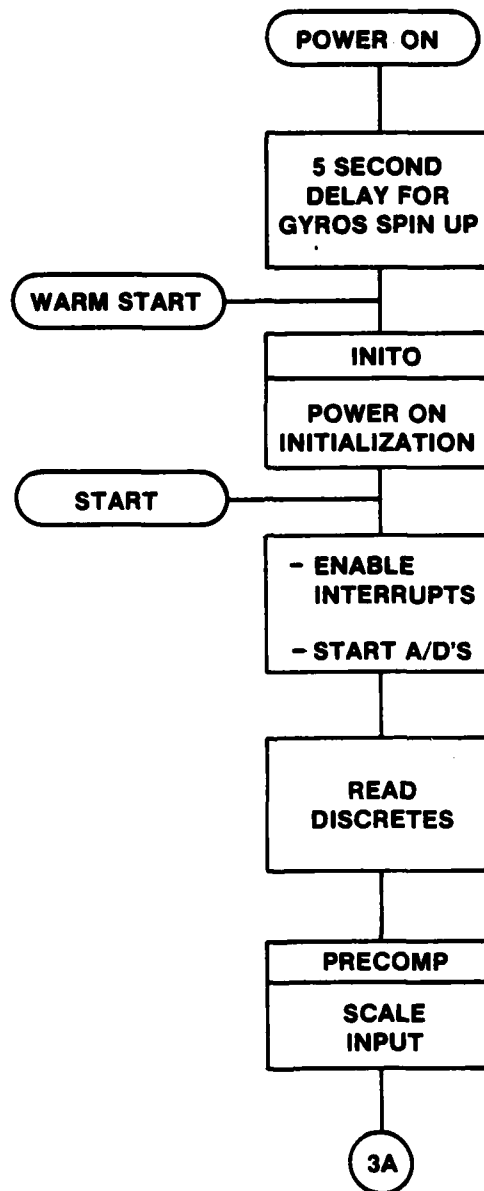


Figure 38. Executive Flow Chart (Sheet 1 of 5)

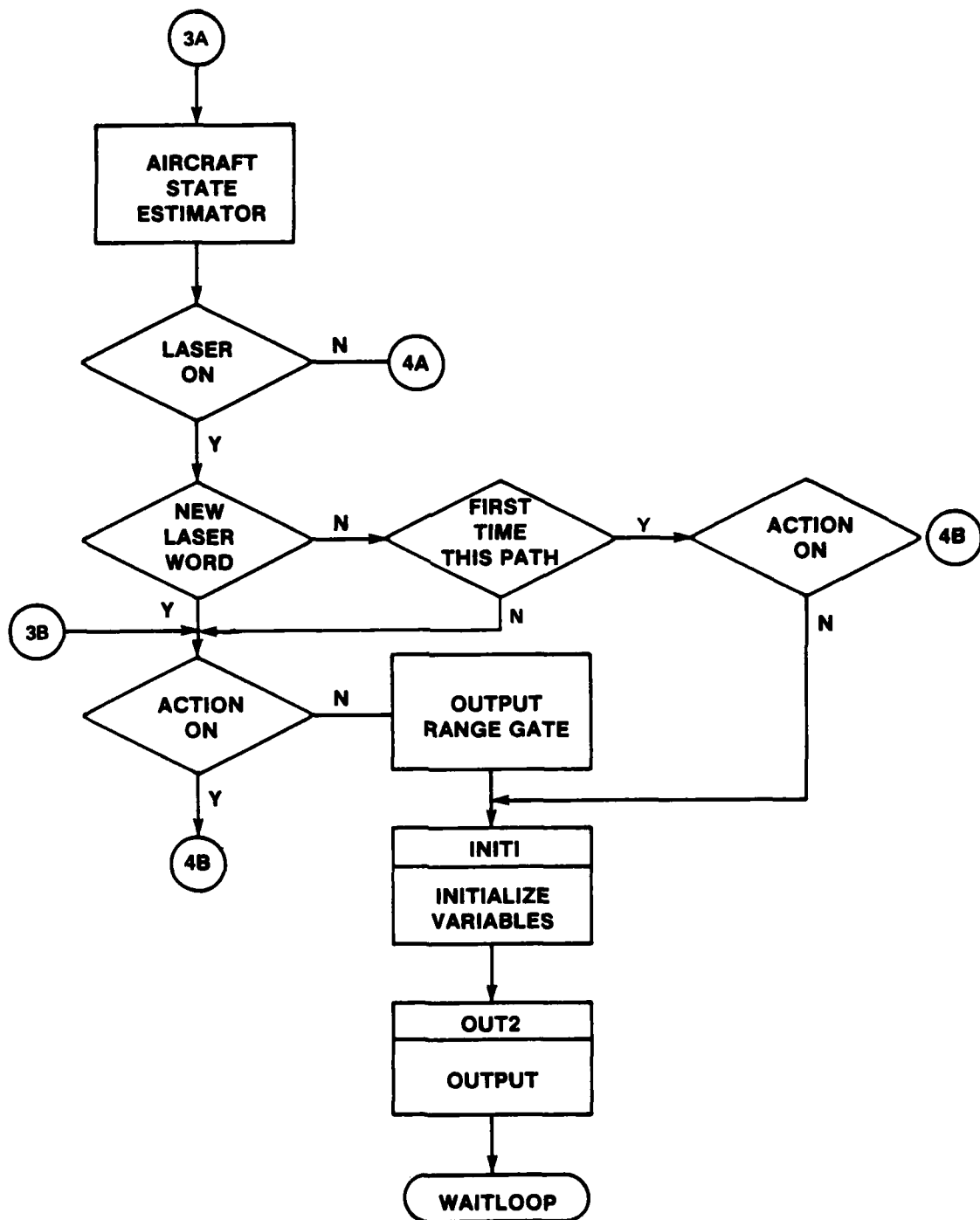


Figure 38. Executive Flow Chart (Sheet 2 of 5)

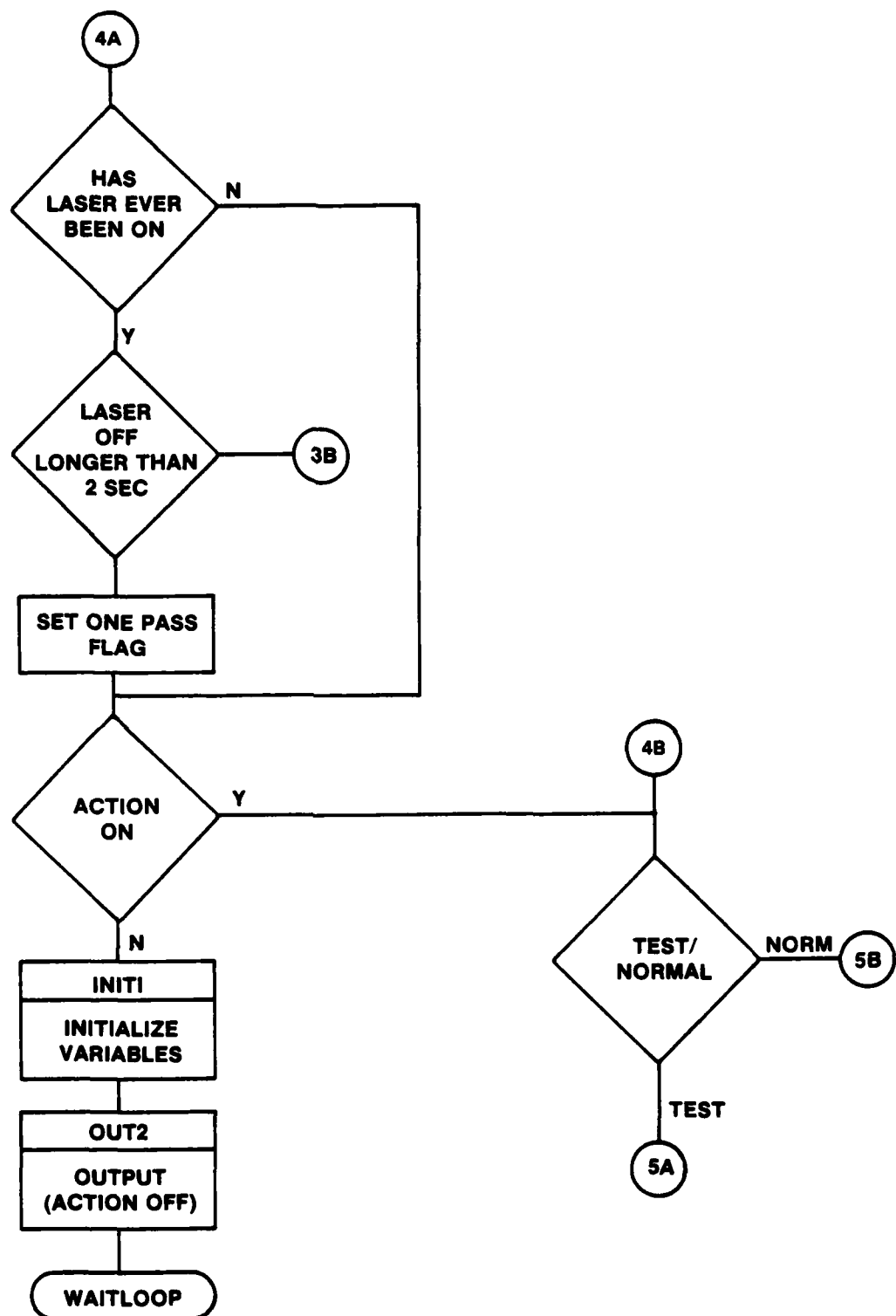


Figure 38. Executive Flow Chart (Sheet 3 of 5)

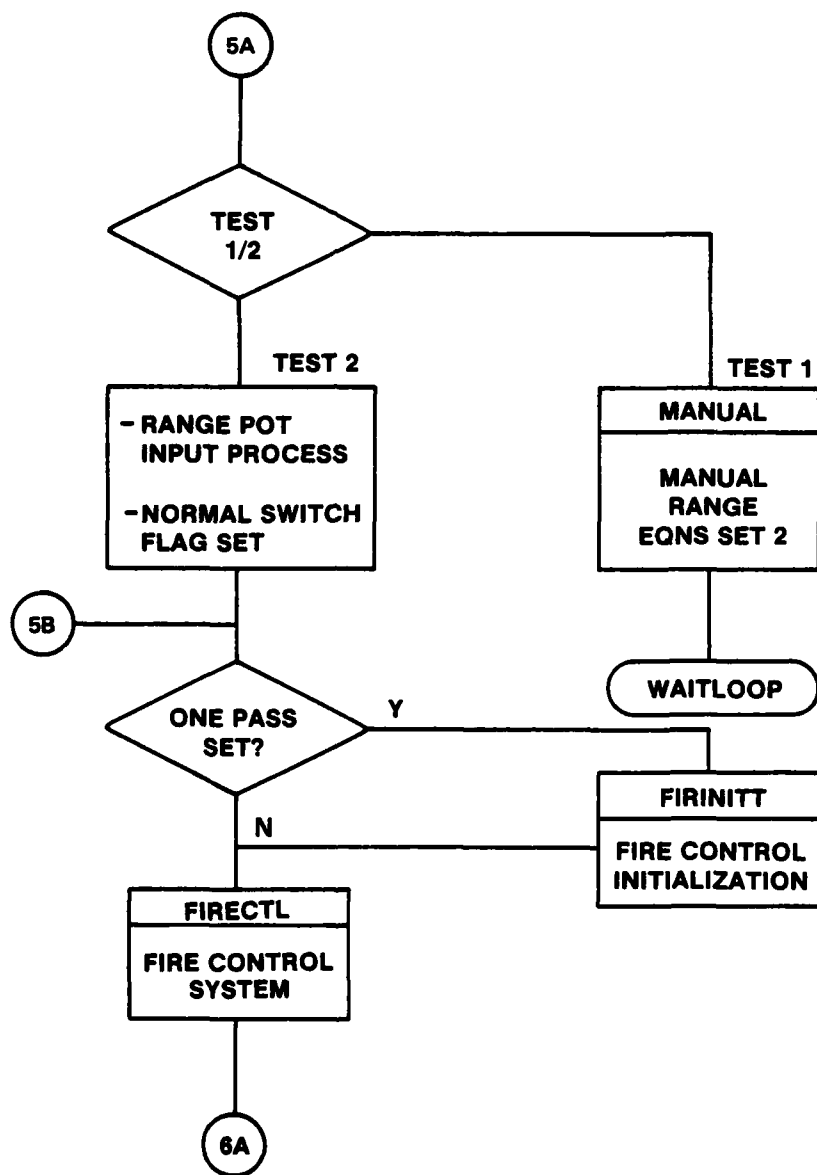


Figure 38. Executive Flow Chart (Sheet 4 of 5)

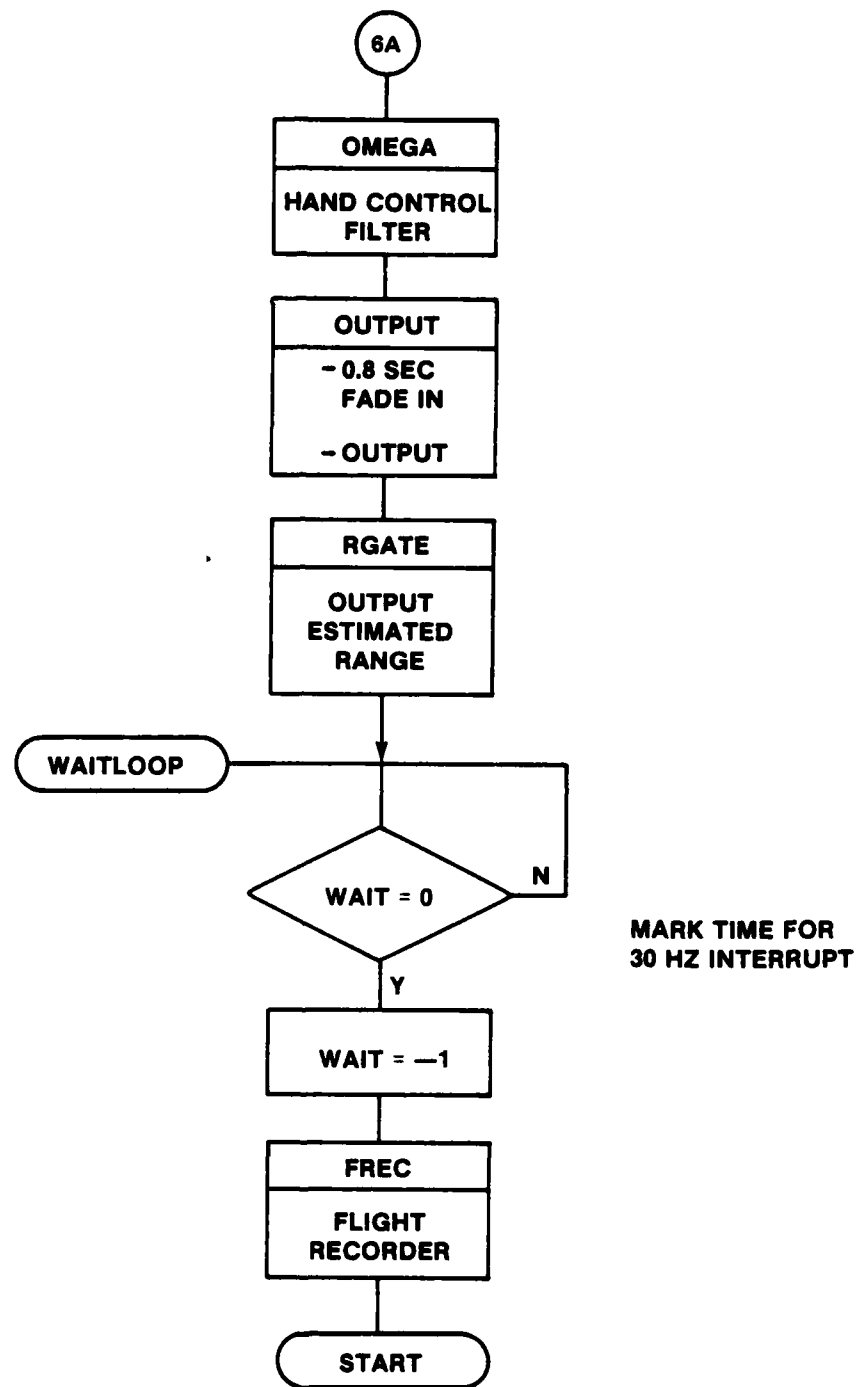


Figure 38. Executive Flow Chart (Sheet 5 of 5)

AIRCRAFT STATE ESTIMATOR

This code was written at GE-Binghamton for original Closed Loop Fire Control Software and has been adopted in air-to-air software without any modification.

INPUT SCALING (PRECOMP)

This subroutine converts the raw input signals to the proper engineering units used in the computer. The scale factors for conversion are listed in Table 4 and are derived from I/O specifications (Appendix B). Direct scaling of the form

$$Y = AX + B$$

is used, where A and B are the scale factor and offset respectively, X is the raw input and Y is the scaled input.

The hand control input uses a two level scaling of the form:

$$Y = AX + B (|X| - C) \cdot \text{SIGN}(X)$$

LASER

This code reads laser word from input/output channel number 12, scales it to meters, saves it for later processing and outputs range gate.

INITIALIZATION

INITO

This subroutine is called on power on at cold and warm starts. It initializes all variables.

INITI

This subroutine is called in No-action (Acquisition) mode. The function of this routine is to initialize all output variables, the aircraft state estimator variables, and computes hand control filtered output for acquisition mode.

FIRINITT

This subroutine is called at first pass after the action switch is closed or if laser has been off for longer than two seconds. It is also called if the flag (IFTACT) has been set according to the logic shown in the range coasting flow chart (Appendix A). The variables are initialized according to the Fire Control Initialization section of Appendix A.

Table 4. THE INPUT SCALE FACTORS

DESCRIPTION	SCALE FACTOR	OFFSET	MAX VALUE	SCALE	UNITS
A/D INPUTS					
Acceleration U	+0.07144047B+3	-	± 145	B-6	Ft/sec ²
V	-.07144047B+3	-	± 145	B-6	Ft/sec ²
W	+0.07144047B+3	-	± 145	B0	Radian
Sin Pitch	1.0	-	$\pm .99$	B0	Radian
Cos Pitch	1.0	-	± 1.0	B0	Radian
Sin Roll	1.0	-	$\pm .99$	B0	Radian
Cos Roll	1.0	-	± 1.0	B0	Radian
Static Pressure	+0.0048828B+2	6.B-9	± 6 to +16	B-9	PSI
Ambient Temperature	+0.09281876B+2	233.16B-9	233.15 to 307.15	B-9	Degree K
Diff. Pressure	+0.000635076B+6	-	0 to 1.3	B-5	PSID
Sight U	1.0	-	± 1	B0	Radian
V	1.0	-	± 1	B0	Radian
W	1.0	-	± 1	B0	Radian
Range Pot	2.4414063B-2	-	0 to 2500	B-12	Meters
Line-of-Sight Gyros S	1.0	-	± 1	B0	Radians
l	1.0	-	± 1	B0	Radians
m	1.0	-	± 1	B0	Radians
Hand Control l, m (See Equation 4.2)	A = 0.07 B0 B = 3.5714B-3 C = 0.5 B0	- - -	± 1	B0	Radian
LASER					
Range	.6263B0	-	0 to 5120	B-12	Meters
IMU Gyros X	.54944B0	-		B-6	Radians
Y	.54978B0	-		B-6	Radians
Z	.54930B0	-		B-6	Radians

HAND CONTROL FILTER (OMEGA)

This subroutine is called in Action mode. The subroutine filters the gunner's hand control commands according to Section 4.5.2 of Appendix A.

TWO STAGE GAIN FOR HAND CONTROL

The two stage gain for hand control (Appendix A, Figure A-1) is computed in a subroutine called DGAIN.

OUTPUT ROUTINES

OUTPUT

This subroutine is called in the Action mode. The function of this routine is to perform a 0.8 second fade in and outputting the variables as outlined in Section 7.12 of the software specification (Appendix A).

OUT2

This subroutine is called in acquisition mode. The routine outputs the variables according to flow chart Figure A-2.

INTERRUPT SERVICE ROUTINE (INTR)

This subroutine performs the following functions:

- Service A. D channels
- Service gyros
- Service real time interrupt
- Build a timer

The following table shows the codes that are read from the Input Transfer Register and designate the type of interrupt:

<u>Interrupt Code</u>	<u>Device</u>
1001	A D converter
1010	Gyro input
1100	Interrupt clock

FLIGHT RECORDER

This subroutine stores real time data on the flight recorder. It is activated by the executive when the tape start switch is turned on at the pilot's control panel. The number of tape starts are

recorded in the variable TAPECNT. Each time the tape start switch on the pilot's control panel is cycled from off to on this variable increments by one. It is ORED into packed discretes variable PDISC and is stored by the flight recorder. The record is written at the end of the seventh iteration. Table 5 shows the format.

Table 5. FLIGHT RECORD FORMAT

DESCRIPTION	NAME	SCALE	UNIT
0 Index Marker (125252)	INDEX	—	—
1 Take Count & Discretes	PDISC	—	—
2 Optical Sight U	SCU	B0	Radians
3 Optical Sight V	SCV	B0	Radians
4 Optical Sight W	SCW	B0	Radians
5 Line-of-Sight Rates S	WS	B0	Radians sec
6 Line-of-Sight l	WL	B0	Radians sec
7 Line-of-Sight m	WM	B0	Radians sec
8 Gunner's Hand Control Trav	HT	B0	Radians
9 Gunner's Hand Control Elev	HE	B0	Radians
10 Laser Range (scaled)	RL	B-12	Meters
11 Static Pressure	PS	B-9	Lbs/in ²
12 Ambient Temperature	TA	B-9	°K
13 Range Measured & Saved	RM	B-12	Meters
14 Rate-Aided Track (Elev)	WEC	B0	Radians
15 Rate-Aided Track (Trav)	WTC	B0	Radians
16 Lead Angle U	BEEU	B0	Radians
17 Lead Angle V	BEEV	B0	Radians
18 Lead Angle W	BEEW	B0	Radians
19 Turret Rate Feed Forward El	RFFE	B0	Radians
20 Turret Rate Feed Forward Az	RFFA	B0	Radians
21 Aircraft Velocity S	VS	B-8	Meters sec
22 Aircraft Velocity l	VL	B-8	Meters sec
23 Aircraft Velocity m	VM	B-8	Meters sec
24 Aircraft Vertical Ref S	ZS	B-10	Radians
25 Aircraft Vertical Ref l	ZL	B-10	Radians
26 Aircraft Vertical Ref m	ZM	B-10	Radians
27 Range Error	ER	B-7	Meters
28 Estimated Range	RES	B-12	Meters
29 Target Velocity s	VETS	B-8	Meters sec
30 Target Accel s	AETS	B-5	Meters sec ²
31 Traverse Error	ET	B-7	Radians
32 Position (Trav)	DEL	B-8	Meters
33 Target Velocity l	VETL	B-8	Meters sec
34 Target Accel l	AETL	B-5	Meters sec ²
35 Elevation Error	EE	B-7	Radians
36 Position (Elev)	DEM	B-8	Meters

Table 5. FLIGHT RECORD FORMAT — Continued

DESCRIPTION	NAME	SCALE	UNIT
37 Target Velocity m	VETM	B-8	Meters/sec
38 Target Accel. m	AETM	B-5	Meters/sec ²
39 Time-of-Flight	TF	B-4	Seconds
40 Future Range	RF	B-12	Meters
41 Gravity Drop	GD	B-12	Meters
42 Iteration Count for TF	ITER	—	—
43 Range as Read from Laser	—	—	—
44 Range Gate	RG	B-12	Meters
45 Initial Range	RI	B-12	Meters
46 Flag for Laser Data	LSRBIT	—	—
47 Sin Elev.	SE	B0	Radians
48 —	Sin Pitch	B0	Radians
49 —	Cos Pitch	B0	Radians

MEMORY LOADER

The General Electric memory loader (Table 6) was used to load the software in CDC 469 memory.

Table 6. MEMORY LOADER

013500	006001	LIS	1	
013501	014177	ENR	177B,10B	
013502	104010	LS	1,10B	377B = Start code
013503	004301	INC	1,10B	
013504	015507	ENR	107B,13B	
013505	105413	LS	1,13B	217 B = Stop code
013506	005701	INC	1,13	
013507	014417	ENR	17B,11B	Mask data
013510	013400	ENR	0,7	Set up for pack
013511	015374	ENR	—4,12B	
013512	142000	OUT	0,4	Advance 1 frame
013513	000417	SRJ	READ,17B	Get a frame
013514	013543			
013515	004144	SKEQ	4,10B	= 377B?
013516	010112	ENP	*-4	No, try again
013517	000416	SRJ	PACK,16B	
013520	013547			
013521	040405	LDR	5,1	Addr in RI
013522	000416	SRJ	PACK,16B	

Table 6. MEMORY LOADER — Continued

013523	013547			
013524	072400	STR.X	0.5	Store via R1
013525	053000	LDR.X	0.6	Read to verify
013526	002546	SKEQ	6.5	R5 = R6?
013527	010127	ENP	*	Halt - bad read
013530	000701	INC	1.1	Bump addr
013531	142000	OUT	0.4	Advance 1 frame
013532	000417	SRJ	READ,17B	
013533	013543			
013534	004104	SKNE	4.10B	= 377B?
013535	010117	ENP	*-16B	Yes, get addr
013536	005504	SKNE	4.13B	No, stop?
013537	010137	ENP	*	Yes, stop
013540	000416	SRJ	PACK+3,16B	No = 217B
013541	013552			
013542	010124	ENP	*-16B	Get data
013543	162004 READ	INP	4.4	Read 1 frame
013544	002061	PJP	*+2,4	
013545	010143	ENP	*-2	
013546	000017	RTN	17B	
013547	142000 PACK	OUT	0.4	Advance 1 frame
013550	000417	SRJ	READ,17B	
013551	013543			
013552	002271	AND	11B,4	Mask data
013553	103404	ADD	4.7	Build word
013554	005301	INC	1.12B	
013555	005062	PJP	*+3,12B	Exit, R12 = +
013556	003723	LS	4.7	4 Bits
013557	010147	ENP	-10B	
013560	042407	LDR	7.5	Transfer
013561	013400	ENR	0.7	Reinitialize
013562	015374	ENR	-4,12B	
013563	000016	RTN	16B	

FIRE CONTROL SYSTEM

FIRECTL is initiated by the executive when the action switch is on and the system mode switch on the pilot's control panel is in the laser position. A detailed flow chart of the subroutine is

shown in Figure 39, accompanied by Table 7 which contains a description of the variables used in the flow chart. The functions performed by the routine can be outlined as follows:

1. Input processing
2. Range coasting logic
3. Target state estimator initialization
4. Filters subroutine
 - Target filters and target extrapolation
 - Time-of-flight subroutine
 - Gun order commands
5. Gun error logic

A discussion of each of these topics is presented in the following paragraphs.

Input Processing

The ownship's velocity vector and the vertical axis direction cosine vector, which were computed in the Aircraft State Estimator, are converted to the s, l, m axes. The resultant vectors are used in the calculation of the fire control equations. For details of the transformation matrix, refer to Section 7.1 of Appendix A.

Range Coasting Logic

This logic tests the new laser variable, LSRBIT, which signifies whether we have received a new range measurement from the laser. The result of the test determines which logic path through the routine is to be taken. If no new data has been read, the code performs range coasting. The laser operates at 10 hertz and the software is executed at 30 hertz, therefore, old data is read two out of every three iterations. Range coasting was designed to provide for a smoother transition between the laser range readings. It accomplishes this by adding to the last measured range delta time multiplied by the estimated range rate.

Two additional tests are included which cause the filter initialization routine, FIRINIT, to be called when the time lapse between new laser readings has exceeded the specified values.

Target State Estimator Initialization

This is the subroutine INIT73, which is called by FIRECTL after two valid range measurements have been received from the laser. It is not called again until FIRINIT is executed. INIT73 initializes the position, velocity, acceleration and residual variables that are used in the three filters of the target state estimator.

Table 7. FIRE CONTROL SYSTEM VARIABLE DESCRIPTIONS

VARIABLE	DESCRIPTION
V_{SLM}	Ownship's velocity vector
Z_{SLM}	Vertical axis direction cosine vector
LSRBIT	New laser data flag
FLG1	First laser reading flag
FLG2	Second laser reading flag
TIM	Time of the first laser reading
TLM	Time of last pass through fire control equations with new laser reading
T	Counter for 30 hertz timing
RI	Storage variable for first laser range
RL	Laser range
RM	Measured laser range for use in fire control equations
\dot{R}_s	Estimated range rate
IFTACT	Flag for first pass through fire control equations
WEC	Rate-aided track in elevation
WTC	Rate-aided track in traverse
RSP	Predicted range from FILTRS
D_{lm}^P	Predicted position of the target in l, m axes
VT_{slm}^P	Predicted velocity of the target in s, l, m axes
AT_{slm}^P	Predicted acceleration of the target in s, l, m axes
τ	Counter for output fade in logic
ERTE	Residual from FILTRS in range, traverse and elevation
\hat{R}_s	Estimated range computed in FILTRS
\hat{D}_{lm}	Estimated position of the target in l, m axes
\hat{VT}_{slm}	Estimated velocity of the target in s, l, m axes
\hat{AT}_{slm}	Estimated acceleration of the target in s, l, m axes
TF	Time-of-flight
RF	Future range
GD	Gravity drop
b_{slm}	Gun position vector
b_{uvw}	Turret lead angle vector
$C_{\lambda A}$	Cosine azimuth lead angle trig function
$S_{\lambda A}$	Sine azimuth lead angle trig function
T_{uvw}	Turret direction cosine command vector
SEG	Sine elevation of the gun
CEG	Cosine elevation of the gun
RFF_A	Rate feed forward in azimuth
RFF_E	Rate feed forward in elevation

Filters Subroutine

The filters subroutine, FILTRS, contains the calculation of the fire control equations as given in the software specifications, Sections 7.4 through 7.8 of Appendix A. The time-of-flight prediction loop is executed in FILTRS by a subroutine jump to TFLT and computation of the gun order commands is done following the return from TFLT. Descriptions of these functions performed by FILTRS are presented below:

a) Target filters and target state extrapolation:

The calculations of the three target filters range, traverse and elevation are performed. In each filter, the residual is computed followed by a calculation of the estimated position, velocity and acceleration in the corresponding axes. The target state extrapolation of the range, traverse and elevation is executed in which the predicted variables are computed and stored. The two components of rate-aided track, WEC and WTC, are found using values calculated in the above filters.

b) Time-of-flight subroutine:

The logic flow of this routine is demonstrated by the flow chart given in Figure A-6. Air density is computed based on the static pressure and ambient temperature. A prediction loop follows in which the time-of-flight and future range vector are calculated. The loop is repeated until time-of-flight converges or until a maximum of five iterations have been executed. When either of these two conditions is reached, the final time-of-flight and future range are stored as TF and RF, respectively, and the subroutine returns to FILTRS.

c) Gun order commands:

This section of FILTRS performs the gravity drop correction and computes turret lead angles and rate feed forwards as specified in Section 7.10 and 7.11 of Appendix A. Gravity drop is computed from TF and RF and is then used to update future range. The calculation of the gun position vector follows in which an iterative loop, GUN-LOOP, is executed four times. The turret lead angle is then found by performing a transformation of axes on the position vector from the s, l, m axes to the u, v, w. The gun turret rate feed forwards, RFFA and RFFE, are the final calculations performed by the fire control equations. These values are stored and FILTRS subroutine returns to FIRECTL.

Gun Error Logic

The software control of the fire inhibit light is accomplished through the gun error logic shown by LOOP6 in the Fire Control System of Figure 39. When the following three conditions are satisfied, the inhibit fire light is turned off:

1. Future range, RF, is less than 1999.
2. The time lapse between the first laser reading after action is cycled on and the present reading is greater than three seconds.
3. There is no gun error signal, which indicates that the turret is synchronized.

FIRE CONTROL CONSTANTS AND VARIABLES

The constants and variables used in the calculations of the fire control equations are located at addresses 003452 through 003700 of the memory map. Indexed addressing is the method used for referencing the desired memory locations. The constants are indexed from ADDR CNST, the address of which lies in Page Zero, and the variables are indexed from either ADDR CNST or ADDR WORK, whose address also lies in page Zero. A description of the constants and variables, along with the dynamic scale factor associated with each variable and its memory address, is presented in Table 8.

Table 8. FIRE CONTROL CONSTANTS AND VARIABLES

APPENDIX A
SPECIFICATION

NAME	SYMBOL	DESCRIPTION	SCALE	ADDRESS
FIRECNST		Variable from which fire control data names are indexed		
T		Counter for 30 HERTZ timing		003452
TIM		Time of first laser reading		003453
TAU	τ	Counter for output fade in logic		003454
FLG1		First laser reading flag		003455
FLG2		Second laser reading flag		003456
ALPHA	α	Constant used in target estimation filters .3	B0	003457
BETA	β	Constant used in target extrapolation filters .7	B0	003460
K1R		Constant gain for range residual .5	B0	003461
K2R		Constant gain for range residual .5	B0	003462
KPS		Constant gain for estimated range .1	B-5	003463
KVS		Constant gain for estimated target velocity (s axis) .15	B-1	003464
KAS		Constant gain for estimated target acceleration (s axis) .15	B+2	003465
K1T		Constant gain for traverse residual .5	B0	003466
K2T		Constant gain for traverse residual .5	B0	003467
KPL		Constant gain for estimated target position (1 axis) .1	B0	003470
KVL		Constant gain for estimated target position (1 axis) .15	B-1	003471
KAL		Constant gain for estimated target acceleration (1 axis) .15	B-1	003472
K1E		Constant gain for elevation residual .5	B+2	003473
K2E		Constant gain for elevation residual .5	B0	003474
KPM		Constant gain for estimated target position (m axis) .1	B0	003475
KVM		Constant gain for estimated target position (m axis) .15	B-1	003476
KAM		Constant gain for estimated target acceleration (m axis) .15	B-1	003477
VB	V_B	Muzzle Velocity	B+2	003500
G		Gravity -9.806	B-11	003501
CS	C_S	Fraction of full stepsize used in time-of-flight iterations .75	B-9	003502
A1	A_1	Constant used in time-of-flight calculation .0004175	B0	003503
A2	A_2	Constant used in time-of-flight calculation .0000001811	B+10	003504
A3	A_3	Constant used in gravity drop calculation 21.3352	B+20	003505
A4	A_4	Constant used in gravity drop calculation -0.221268	B-8	003506
EPS	ϵ	Epsilon used in time-of-flight convergence test .0015	B0	003507
			B0	003510

Table 8. FIRE CONTROL CONSTANTS AND VARIABLES -- Continued

NAME	APPENDIX A SPECIFICATION SYMBOL	DESCRIPTION	SCALE	ADDRESS
KG	KG	Constant used to relate hand control inputs to tracking error	B-2	003511
FOURTEN		Not used .4	B0	003512
RFTEST		Constant used in time-of-flight logic for limit test on future range	B-12	003513
KX		Not used		003514
ONETH		Constant used in gravity drop correction	B-10	003515
TWOTHOU		Constant used in time-of-flight calculation $1/2000 = .0005$	B+10	003516
C25		Constant used in output fade in logic	B-2	003517
B		Not used .1	B0	003520
SFACTORS		Variable from which scale factors are indexed		003521
HSCL		Not used		003522
RSCALE		Range input scale factor .6263	B0	003523
BUSCALE		Lead angles output scale factor 3.355704698	B-2	003524
WSCALE		Rate-aided track output scale factor .6666	B0	003525
FIREWORK		Variable from which fire control variables are indexed		003526
CEL	CE	Cosine elevation of the sight angle	B-1	003527
SAZ	SA	Sine azimuth of the sight	B0	003530
CAZ	CA	Cosine azimuth of the sight	B0	003531
T11		11 Component of uvw to slm transformation matrix	B0	003532
T12		12 Component of uvw to slm transformation matrix	B0	003533
T21		21 Component of uvw to slm transformation matrix	B0	003534
T31		31 Component of uvw to slm transformation matrix	B-1	003535
T32		32 Component of uvw to slm transformation matrix	B-1	003536
BV		Not used	B-11	003537
BEE	b	Constant used in range extrapolation calculation .1	B0	003540
BEES	b _s	s component of gun position vector	B0	003541
BEEL	b _l	l component of gun position vector	B0	003542
BEEB	b _m	m component of gun position vector	B0	003543
VS	V _s	S component of ownship's velocity vector	B-8	003544
VL	V _l	L component of ownship's velocity vector	B-8	003545
VM	V _m	M component of ownship's velocity vector	B-8	003546
ZS	Z _s	S component of ownship's vertical vector	B-10	003547
ZL	Z _l	L component of ownship's vertical vector	B-10	003550

Table 8. FIRE CONTROL CONSTANTS AND VARIABLES -- Continued

APPENDIX A
SPECIFICATION

NAME	SYMBOL	DESCRIPTION	SCALE	ADDRESS
ZM	Z_m	M component of ownship's vertical vector	B-10	003551
VTSP	VTSP	Predicted target velocity in s direction	B-8	003552
VTMP	VTMP	Predicted target velocity in elevation	B-8	003553
VTLP	VTLP	Predicted target velocity in traverse	B-8	003554
ER	ER	Filtered range residual	B-7	003555
ER1	ER1	Range residual	B-7	003556
RM	RM	Measured laser range for use in fire control equations	B-12	003557
RL	RL	Laser range	B-12	003560
RG	RG	Laser range gate which is outputted to the laser ranger	B-12	003561
RSP	RSP	Predicted range	B-12	003562
R1	R1	Storage variable for first laser range	B-12	003563
RES	\hat{R}_s	Estimated range computed in FILTRS	B-12	003564
VETS	\hat{V}_T	Estimated target velocity in s direction	B-8	003565
AETS	\hat{A}_T	Estimated target acceleration in s direction	B-5	003566
DMP	DMP	Predicted position in elevation	B-8	003567
DLP	DLP	Predicted position in traverse	B-8	003570
ET	E_T	Filtered traverse residual	B-7	003571
ET1	E_{T1}	Traverse residual	B-7	003572
DEL	D_1	Estimated position in traverse	B-8	003573
VETL	\hat{V}_{T1}	Estimated target velocity in traverse	B-8	003574
AETL	\hat{A}_{T1}	Estimated target acceleration in traverse	B-5	003575
EE	EE	Filtered elevation residual	B-7	003576
EE1	E_{E1}	Elevation residual	B-7	003577
DEM	\hat{D}_M	Estimated position in elevation	B-8	003600
VETM	\hat{V}_{TM}	Estimated target velocity in elevation	B-8	003601
AETM	\hat{A}_{TM}	Estimated target acceleration in elevation	B-5	003602
DPS	DPS	Predicted position in s direction	B-8	003603
ATSP	ATSP	Predicted target acceleration in s direction	B-5	003604
CBEE	B	Norm of the gun position vector	B-1	003605
ATLP	ATLP	Predicted target acceleration in traverse	B-5	003606
ATMP	ATMP	Predicted target acceleration in elevation	B-5	003607
WEC	WEC	Rate-aided track in elevation	B0	003610

Table 8. FIRE CONTROL CONSTANTS AND VARIABLES -- Continued

APPENDIX A SPECIFICATION		DESCRIPTION		SCALE	ADDRESS
NAME	SYMBOL				
WTC	W_{TC}	Rate-aided track in traverse		B0	003611
DTF	ΔT_F	Delta time-of-flight		B-4	003612
TF	T_F	Time-of-flight		B-4	003613
TFO	T_{FO}	Time-of-flight from previous iteration		B-4	003614
RFS	R_{Fs}	s component of future range		B-12	003615
RFL	R_{Fl}	l component of future range		B-12	003616
RFM	R_{Fm}	m component of future range		B-12	003617
RF	R_F	Future range		B-12	003620
GD	G_D	Gravity drop		B-12	003621
BEEU	b_u	U component of gun turret lead angle		B0	003622
BEEV	b_v	V component of gun turret lead angle		B0	003623
BEEW	b_w	W component of gun turret lead angle		B0	003624
CLA	$C_{\lambda A}$	Cosine azimuth lead angle		B0	003625
SLA	$S_{\lambda A}$	Sine azimuth lead angle		B0	003626
TU	T_u	U component of turret direction cosine command		B-1	003627
TV	T_v	V component of turret direction cosine command		B-1	003630
TW	T_w	W component of turret direction cosine command		B-1	003631
TM	T_M	Norm of turret direction cosine command vector		B-1	003632
SEG	SEG	Sine elevation of the gun turret		B-1	003633
CEG	CEG	Cosine elevation of the gun turret		B-1	003634
LSRKNT		Determines the elapsed real time			003635
PKNT		First pass flag for old laser data used in laser range gate logic			003636
IFTACT		Flag for first pass through fire control equations			003637
LSRBIT		New laser data flag			003640
HT	h_T	Gunner's hand station command in traverse		B0	003641
HE	h_E	Gunner's hand station command in elevation		B0	003642
WS	ω_s	Line-of-sight rate in s direction		B0	003643
WL	ω_l	Line-of-sight rate in traverse		B0	003644
WM	ω_m	Line-of-sight rate in elevation		B0	003645
LSR		Not used			003646
LFLC		Not used			003647

Table 8. FIRE CONTROL CONSTANTS AND VARIABLES — Continued

APPENDIX A SPECIFICATION		DESCRIPTION		SCALE ADDRESS	
NAME	SYMBOL				
RFFA	RFFA	Azimuth rate feed forward		B-1	003650
RFFE	RFFE	Elevation rate feed forward		B-1	003651
MASKS		Variable from which masks are indexed			003652
M7777		Bit suppressing mask			003653
M77700		Bit suppressing mask			003654
M177760		Bit suppressing mask			003655
TLM		Time of last pass through fire control equations with new laser reading			003656
CBV	B _v	Bullet velocity = ownship's + muzzle velocity		B-11	003657
BSO	b _{s0}	Storage variable for s component of gun position vector		B0	003660
BLO	b _{l0}	Storage variable for l component of gun position vector		B0	003661
BMO	b _{m0}	Storage variable for m component of gun position vector		B0	003662
ONEHALF		Not used			003663
T22		22 Component of u, v, w to s, l, m transformation matrix		B0	003664
RFST	R _{FsT}	Future range minus gravity drop - s component		B-12	003665
RFLT	R _{FlT}	Future range minus gravity drop - l component		B-12	003666
RFMT	R _{FmT}	Future range minus gravity drop - m component		B-12	003667
SE	S _E	Sine elevation of sight angle		B-1	003670
HTEMPE	H _{TEMPE}	Temporary storage for elevation hand control used in hand control filter		B0	003671
HTEMPT	H _{TEMPT}	Temporary storage for traverse hand control used in hand control filter		B0	003672
HFE	H _{FE}	Filtered hand control in elevation		B0	003673
HFT	H _{FT}	Filtered hand control in traverse		B0	003674
K1H	K _{1H}	Constant gain used in hand control filter .0056347		B0	003675
K2H	K _{2H}	Constant gain used in hand control filter .99437		B0	003676
K3H	K _{3H}	Constant gain used in hand control filter .82653		B0	003677
K4H	K _{4H}	Constant gain used in hand control filter .17347		B0	003700

APPENDIX A

**AIR-TO-AIR FIRE CONTROL
SOFTWARE SPECIFICATION**

CONTRACT DAAK10-79-C-0028

1.0 Scope

This specification covers the requirements for the changes to the Closed Loop Fire Control System (CLFCS) software which are required by Contract number DAAK10-79-C-0028, "Air to Air Helicopter Fire Control Equations and Software Generation".

The resulting software must run on a CDC469 computer. It shall compute the quantities needed to output the proper gun turret lead angles and rate feed forward signals, as well as rate aided track signals to the tracking sight.

2.0 Inputs

The following signals shall be added as inputs to the CDC 469 computer, in addition to those already used for the CLFCS program.

2.1 Optical Sight Direction Cosine Vector

Rev. 4/4/79 Rev. 10/12/79

Three electrical components of the gunner's sightline vector are provided. These are 400 Hz analog voltages with the following gradients:

$$\begin{aligned} S_U &= 10 \cos E_S \cos A_S && \text{Rms, volts} \\ S_V &= -10 \cos E_S \sin A_S && \text{Rms, volts (Azimuth Positive Right)} \\ S_W &= -10 \sin E_S && \text{Rms, volts (Elevation Positive Down)} \end{aligned}$$

where E_S and A_S are the sight elevation and azimuth angles respectively.

2.2 Line of Sight Rates - $\omega_S, \omega_L, \omega_M$

Rev. 4/23/79

The traverse and elevation gyros ω_L and ω_M must be inverted in sign before use in the following equations.

2.3 Gunner's Hand Station Inputs - h_T , h_E Rev. 4/23/79 Rev. 10/12/79

The traverse command, h_T , must be inverted in sign. In addition, a two stage gain must be provided for each axis as shown in Figure A-1.

2.4 Laser Range Measurement - R_L

2.5 Laser New Data Flag

2.6 Test/Normal Switch

2.7 Test 1/Test 2 Switch

2.8 Target Insert Flag - TI

Rev. 4/4/79

2.9 Pilot Input Range - R_P

Rev. 4/4/79

2.10 Laser/Manual Switch

Rev. 4/23/79

3.0 Outputs

Rev. 6/7/79

The following outputs shall be provided by the modified software. All except the Not Ready Light and Laser Range Gate shall be zeroed in subroutine Initialization 1 which is shown in Figures A-2 and A-4.

3.1 Not Ready Light

This red light in the sight is lit according to the logic specified in Section 7.

3.2 Rate Aided Track - ω_{EC} , ω_{TC}

These commands are computed according to the equations in Section 7.8 and 7.12.

3.3 Gun Turret Lead Angle - b_u , b_v , b_w

These commands are computed according to the equations in Section 7.10.2 and 7.12.

3.4 Gun Turret Rate Feed Forward - RFF_E , RFF_A

These commands are computed according to the equations in Section 7.11 and 7.12.

3.5 Laser Range Gate - R_G

Rev. 4/4/79

This signal is output to the laser ranger as described in the "Modified CIU Functional Description", and in the "I/O Specification for the Modified

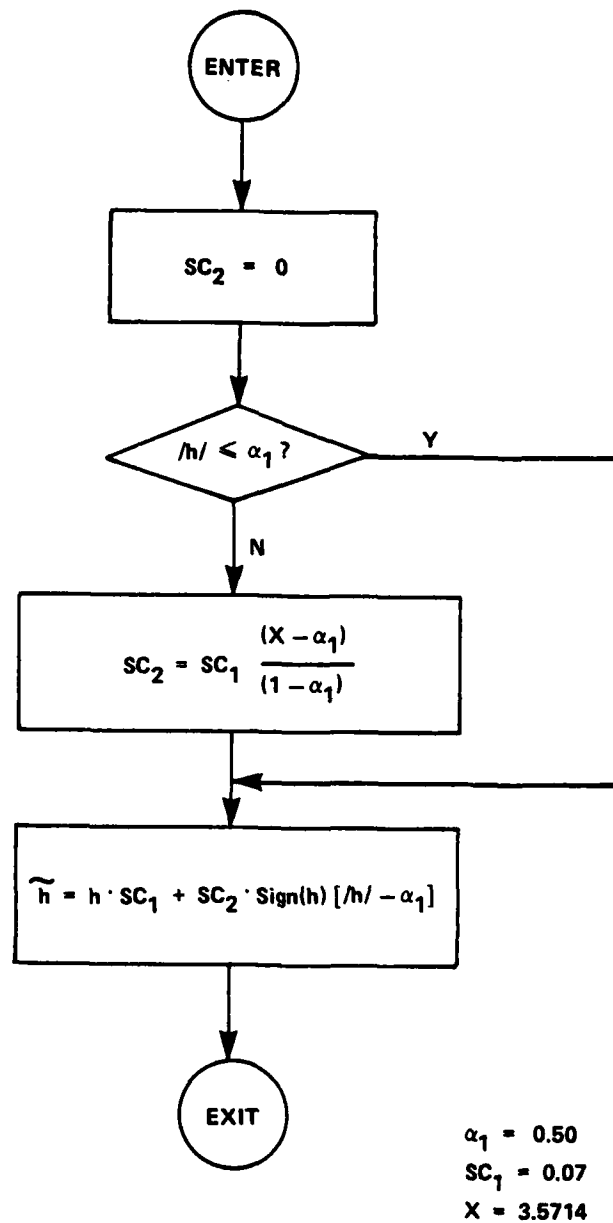


Figure A-1. Hand Control Two Stage Gain

CIU Hardware". The logic is specified in Figures A-2 and A-3 which show that the range gate is calculated either from the measured range R_L , or the estimated range, \hat{R}_S .

4.0 Executive Flow Chart

Rev. 4/4/79

Figure A-3 is a top level flow chart which depicts the interface between the existing CLFCS software and the modifications and additions which are contained in this specification. It is based on the executive flow chart from "Closed Loop Fire Control System Final Report" which is included here as Figure A-4 for comparison purposes.

4.5 Hand Control Filters

Added 10/12/79

Control of the sight is done entirely by software both in the acquisition (non-action) and full fire control with rate aided track (Action) modes. In all cases the total sight rate command is output from the computer on the rate aided track channels, ω_{EC} and ω_{TC} .

4.5.1 Nonaction Mode

In this mode the gunner's hand station commands h_E and h_T are filtered according to the equations in Section 4.5.3. (See Figure A-2). The filters must be initialized with the values.

$$\begin{aligned}\omega_{EC} &= h_E \\ \omega_{TC} &= -h_T.\end{aligned}$$

After this initialization the outputs are calculated from the filter outputs as

$$\begin{aligned}\omega_{EC} &= H_{FE} \\ \omega_{TC} &= -H_{FT}.\end{aligned}$$

4.5.2 Action Mode

The gunner's hand station commands are filtered according to the equations in Section 4.5.3 as shown in Figure A-3. No filter initialization is done in

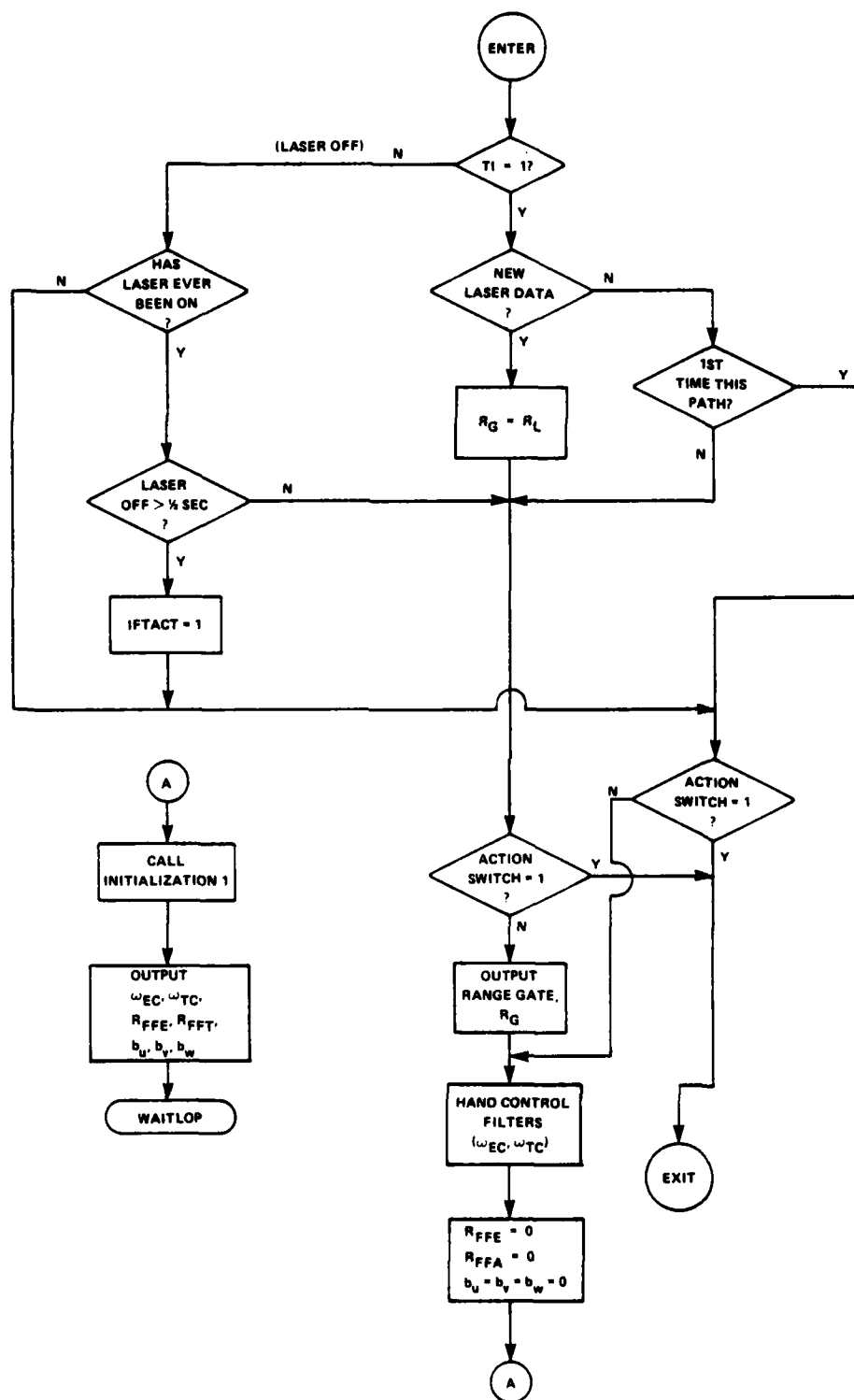


Figure A-2. Laser Range Gate Logic

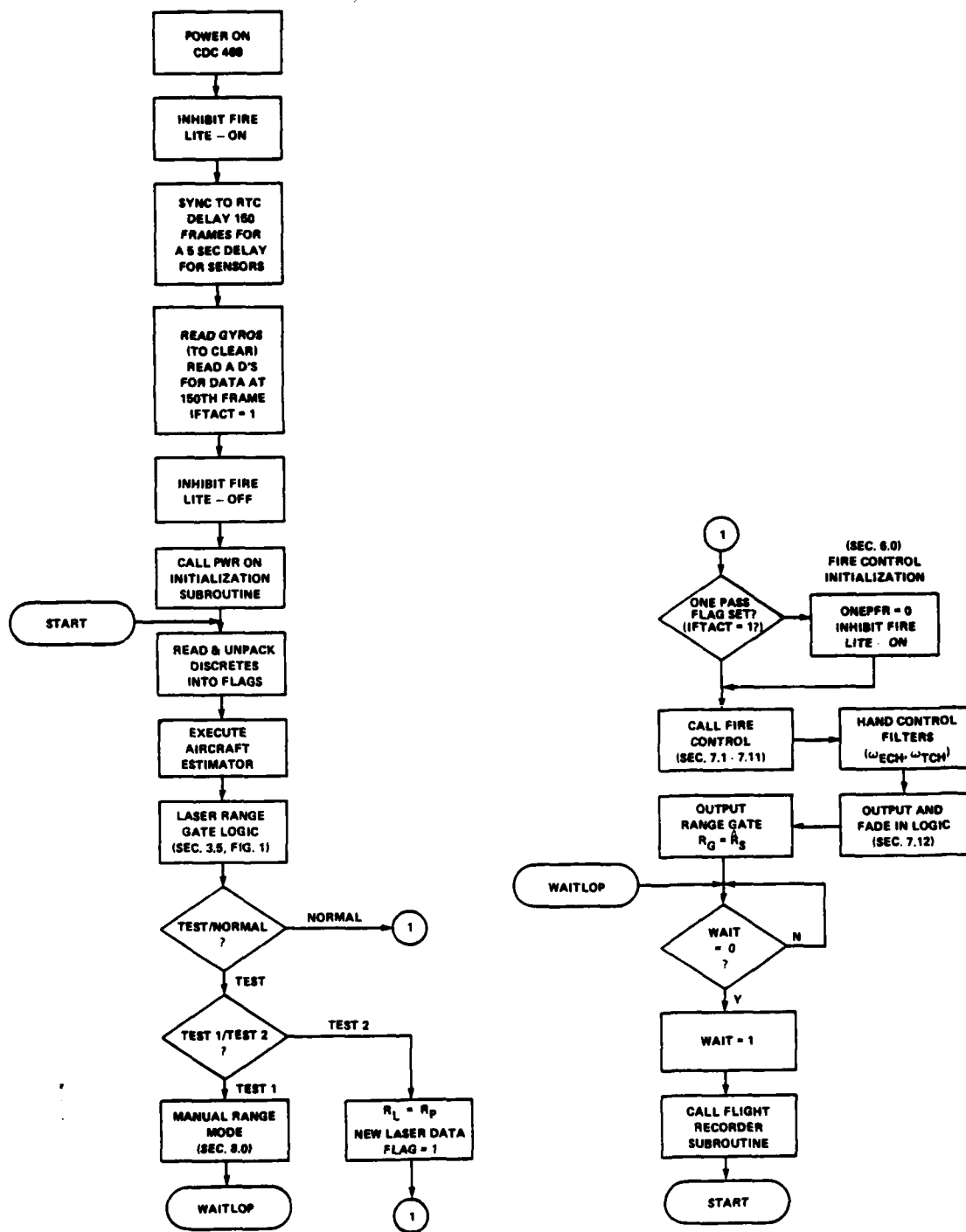


Figure A-3. Modified CLFCS Executive Flow Chart

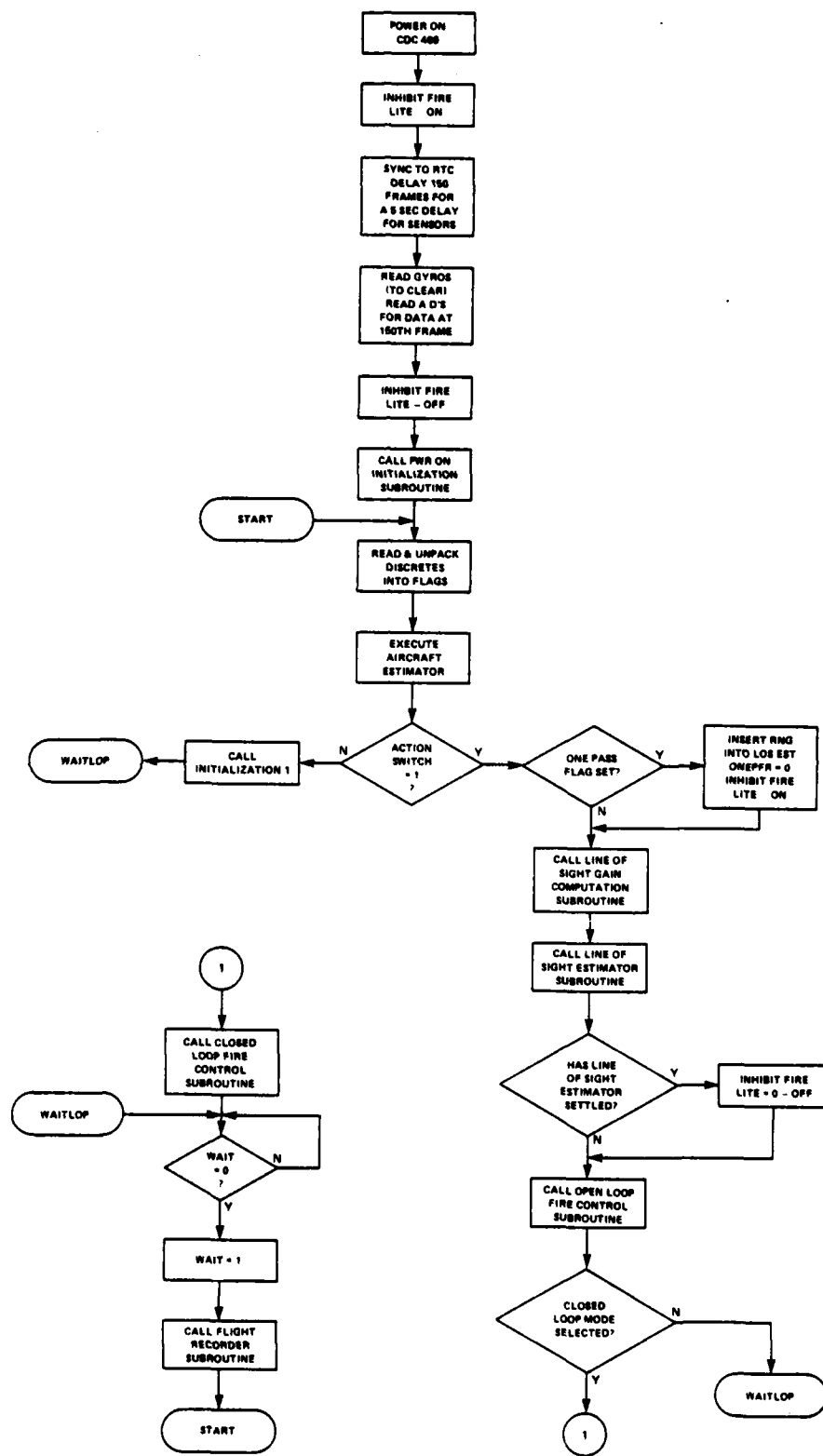


Figure A-4. Original CLFCS Executive Flow Chart

this mode. The filter outputs are calculated as

$$\omega_{ECH} = H_{FE}$$

$$\omega_{TCH} = -H_{FT}$$

and used in the fade in and output logic as specified in Section 7.12.

4.5.3 Filter Equations

$$H_{TEMPE} = K_{1H} h_E + K_{2H} H_{TEMPE}$$

$$H_{FE} = K_{4H} h_E + K_{3H} H_{TEMPE}$$

$$H_{TEMPT} = K_{1H} h_T + K_{2H} H_{TEMPT}$$

$$H_{FT} = K_{4H} h_T + K_{3H} H_{TEMPT}$$

where

$$K_{1H} = .0056347$$

$$K_{2H} = .99437$$

$$K_{3H} = .82653$$

$$K_{4H} = .17347$$

5.0 Interface With Other Programs

The following variables are calculated by the existing "Aircraft Estimator" subroutine and shall be made available for use in the Fire Control Equations specified in Section 6.0.

5.1 Own Ship's Velocity Vector

The three components of estimated own ship's velocity are calculated as aircraft state vector components X_7 , X_8 , and X_9 . These values are known as \hat{V}_u , \hat{V}_v , and \hat{V}_w respectively. They have units of feet per second.

5.2 Vertical Axis Direction Cosine Vector

The three components of the estimated vertical vector are calculated as

aircraft state vector components X_{10} , X_{11} , and X_{12} . These values are known as \hat{Z}_u , \hat{Z}_v , and \hat{Z}_w . They have units of milliradians.

The following inputs are read by the existing "Aircraft State Estimator" subroutine and must be passed to the Air Data Calculations specified in Section 7.9.1

5.3 Static Pressure - P_S

5.4 Ambient Temperature - T_A

6.0 Fire Control Initialization

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Rev. 10/12/79

This logic is performed the first pass after the action switch is closed, as indicated in Figure A-3. It includes all of the code already there, with the sole deletion of the reading of the range pot and using it to initialize the range estimate. In addition, the following computations shall be performed.

$T_{IM} = 0$	$K_{IT} = 0.5$	$V_B = 1045$
$\tau = 0$		$B_V = V_B$
$t = 0$	$K_{2T} = 1 - K_{1T}$	$G = -9.806$
$FLG1 = 0$	$K_{Pl} = 0.1$	$C_S = 0.75$
$FLG2 = 0$	$K_{Vl} = 0.15$	$A_1 = 0.4175 \times 10^{-3}$
$\alpha = 0.3$	$K_{Al} = 0.15$	$A_2 = 0.1811 \times 10^{-6}$
$\beta = 1 - \alpha$	$K_{1E} = 0.5$	$\epsilon = 0.0015$
$K_{1R} = 0.5$	$K_{2E} = 1 - K_{1E}$	$A_3 = 21.3352$
$K_{2R} = 1 - K_{1R}$	$K_{PM} = 0.1$	$A_4 = -0.0221268$
$K_{PS} = 0.1$	$K_{VM} = 0.15$	$K_G = 3.0$
$K_{VS} = 0.15$	$K_{AM} = 0.15$	$IFTACT = 0$
$K_{AS} = 0.15$	$b = 0.1$	$W_{SCL} = 1.0$
$b_S = 1$	$b_l = 0$	$b_M = 0$
$\omega_{EC} = 0$	$\omega_{TC} = 0$	

7.0 Fire Control Equations

Rev. 4/4/79

The logic and equations in this section should be implemented in the same order as written. These equations correspond to the block in Figure A-3 labeled "Call Fire Control".

The equations are written here in an engineering form designed to reveal the functional flow of information. However this is not necessarily the most computationally efficient. A reasonable amount of effort should be expended to optimize the time efficiency of the computations.

In addition, the scaling of each variable must be kept in mind as each line of code is written in order to maintain a high level of computational precision. It may be helpful in this regard to perform a units scaling so that the absolute values of the variables fall more closely in the same order of magnitude. For instance, distances in kilometers and angles and unit vectors in milliradians would be a logical choice.

7.1 Input Processing

7.1.1 Normalize Sight Direction Cosine Vector and Invert Elevation & Azimuth

Rev. 10/12/79

$$K_V = (S_U^2 + S_V^2 + S_W^2)^{1/2}$$

$$S_U = \frac{S_U}{K_V}$$

$$S_V = \frac{-S_V}{K_V} \quad (\text{Azimuth Positive Left})$$

$$S_W = \frac{-S_W}{K_V} \quad (\text{Elevation Positive Up})$$

7.1.2 Compute Sine and Cosine of Sight Angles

$$S_E = S_W \quad (\text{Elevation Positive Up})$$

$$C_E = (S_U^2 + S_V^2)^{1/2}$$

$$S_A = \frac{S_V}{C_E}$$

$$C_A = \frac{S_U}{C_E}$$

7.1.3 Coordinate Transform Matrix - uvw to slm

Rev. 10/12/79

$$T_{11} = S_U$$

$$T_{12} = S_V$$

$$T_{13} = S_W$$

$$T_{21} = -S_A$$

$$T_{22} = C_A$$

$$T_{31} = -S_E C_A$$

$$T_{32} = -S_E S_A$$

$$T_{33} = C_E$$

7.1.4 Convert Own Ship's Velocity and Vertical to slm

Rev. 10/12/79

$$V_S = 0.3049 (T_{11} \hat{V}_U + T_{12} \hat{V}_V + T_{13} \hat{V}_W)$$

$$V_L = 0.3048 (T_{21} \hat{V}_U + T_{22} \hat{V}_V)$$

$$V_M = 0.3048 (T_{31} \hat{V}_U + T_{32} \hat{V}_V + T_{33} \hat{V}_W)$$

$$Z_S = T_{11} \hat{Z}_U + T_{12} \hat{Z}_V + T_{13} \hat{Z}_W$$

$$Z_L = T_{21} \hat{Z}_U + T_{22} \hat{Z}_V$$

$$Z_M = T_{31} \hat{Z}_U + T_{32} \hat{Z}_V + T_{33} \hat{Z}_W$$

7.2 Range Coasting

Rev. 10/12/79

The Range Coasting Logic provides the following functions:

- A. Target State Estimator initialization after two valid range measurements have been made.
- B. Extrapolation of the 10 Hertz Laser range data to 30 Hertz - the data rate of the Fire Control calculations.
- C. Extend the extrapolation up to 9.0 seconds to "coast" through periods of missing laser range data.

This logic should be implemented according to the flowchart in Figure A-5.

7.3 Target State Estimator Initialization

Rev. 6/7/79

These computations initialize the Target State Estimator which consists of the Range, Traverse, and Elevation Filters as specified in Sections 7.4, 7.5 and 7.6. This initialization is performed after two laser range measurements have been obtained within a 1.1 second interval, as specified in Figure A-5.

$$R_{SP} = R_M$$

$$V_{TSP} = \frac{R_M - R_1}{\tau - T_{IM}} + V_S$$

$$V_{TMP} = -\omega_\ell R_M + V_M$$

$$V_{TlP} = \omega_M R_M + V_\ell$$

$$\tau = 0$$

$$A_{TSP} = 0$$

$$\epsilon_R = 0$$

$$D_{lP} = 0$$

$$A_{TlP} = 0$$

$$\epsilon_T = 0$$

$$D_{MP} = 0$$

$$A_{TMP} = 0$$

$$\epsilon_E = 0$$

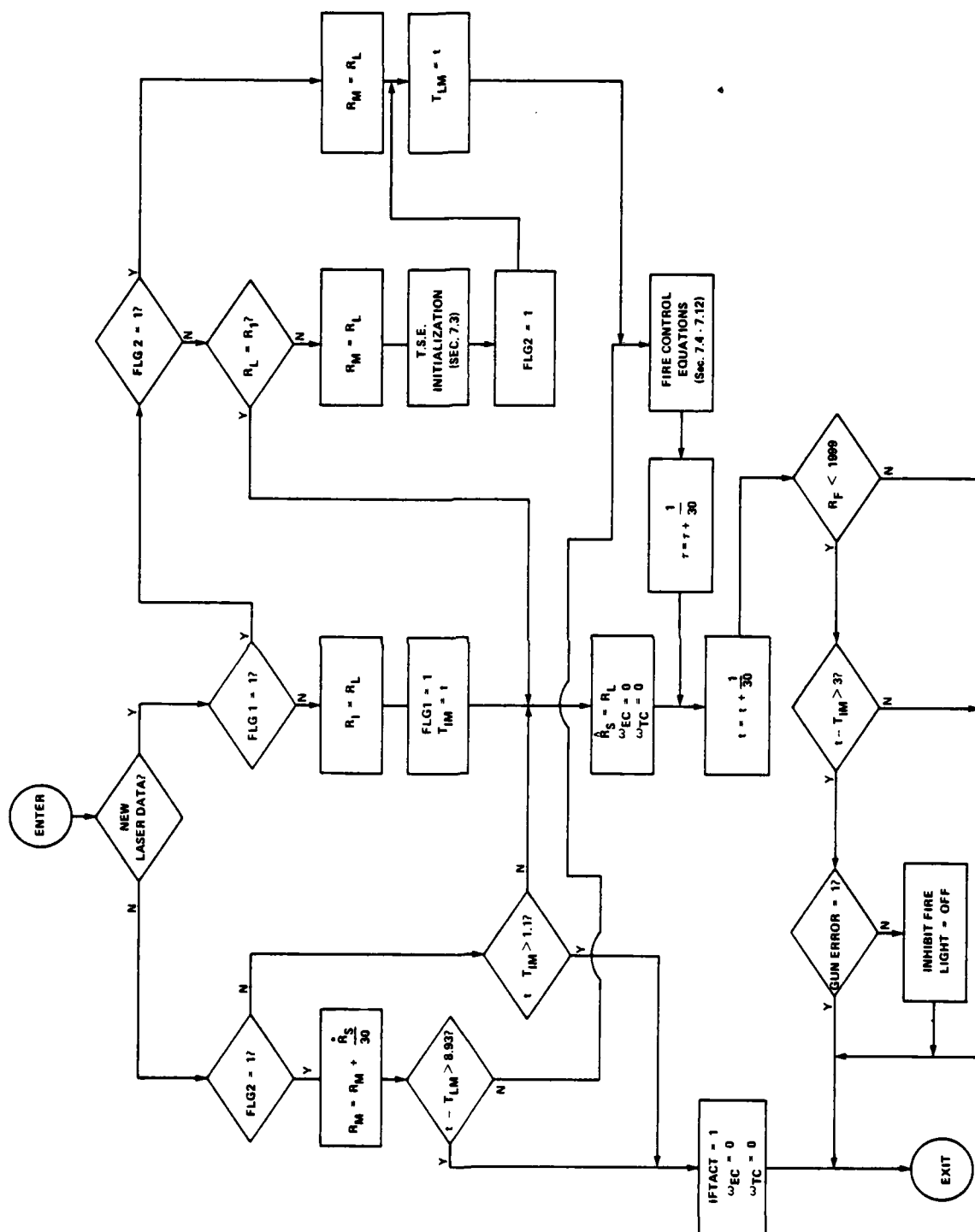


Figure A-5. Range Coasting Logic

7.4 Target Range Filter

7.4.1 Range Residual and Noise Filter

$$\begin{aligned}\epsilon_R^1 &= R_M - R_{SP} \\ \epsilon_R &= K_{1R} \epsilon_R^1 + K_{2R} \epsilon_R\end{aligned}$$

7.4.2 Range Estimation

$$\begin{aligned}\hat{R}_S &= R_{SP} + K_{PS} \epsilon_R + \frac{\alpha}{30} [V_{TSP} - V_S - \omega_\ell D_{MP} + \omega_M D_{\ell P}] \\ \hat{V}_{TS} &= V_{TSP} + K_{VS} \epsilon_R + \frac{\alpha}{30} [A_{TSP} - \omega_\ell V_{TMP} + \omega_M V_{T\ell P}] \\ \hat{A}_{TS} &= A_{TSP} + K_{AS} \epsilon_R + \frac{\alpha}{30} [-b A_{TSP} - \omega_\ell A_{TMP} + \omega_M A_{T\ell P}]\end{aligned}$$

7.5 Target Traverse Filter

7.5.1 Traverse Residual and Noise Filter

Rev. 4/4/79

$$\begin{aligned}\epsilon_T^1 &= \frac{h_T}{K_G} \hat{R}_S - D_{\ell P} \\ \epsilon_T &= K_{1T} \epsilon_T^1 + K_{2T} \epsilon_T\end{aligned}$$

7.5.2 Traverse Estimation

$$\begin{aligned}\hat{D}_\ell &= D_{\ell P} + K_{P\ell} \epsilon_T + \frac{\alpha}{30} [V_{T\ell P} - V_\ell - \omega_M R_{SP} + \omega_S D_{MP}] \\ \hat{V}_{T\ell} &= V_{T\ell P} + K_{V\ell} \epsilon_T + \frac{\alpha}{30} [A_{T\ell P} - \omega_M V_{TSP} + \omega_S V_{TMP}] \\ \hat{A}_{T\ell} &= A_{T\ell P} + K_{A\ell} \epsilon_T + \frac{\alpha}{30} [-b A_{T\ell P} - \omega_M A_{TSP} + \omega_S A_{TMP}]\end{aligned}$$

7.6 Target Elevation Filter

7.6.1 Elevation Residual and Noise Filter

Rev. 4/4/79

$$\begin{aligned}\epsilon_E^1 &= \frac{h_E}{K_G} \hat{R}_S - D_{MP} \\ \epsilon_E &= K_{1E} \epsilon_E^1 + K_{2E} \epsilon_E\end{aligned}$$

7.6.2 Elevation Estimation

$$\hat{D}_M = D_{MP} + K_{PM} \epsilon_E + \frac{\alpha}{30} [V_{TMP} - V_M - \omega_S D_{LP} + \omega_L R_{SP}]$$

$$\hat{V}_{TM} = V_{TMP} + K_{VM} \epsilon_E + \frac{\alpha}{30} [A_{TMP} - \omega_S V_{TLP} + \omega_L V_{TSP}]$$

$$\hat{A}_{TM} = A_{TMP} + K_{AM} \epsilon_E + \frac{\alpha}{30} [-b A_{TMP} - \omega_S A_{TLP} + \omega_L A_{TSP}]$$

7.7 Target State Extrapolation

7.7.1 Range Extrapolation

Rev. 4/4/73

$$D_{PS} = \frac{1}{30} [\hat{V}_{TS} - V_S - \omega_L \hat{D}_M + \omega_M \hat{D}_L]$$

$$R_{SP} = \hat{R}_S + \beta D_{PS}$$

$$V_{TSP} = \hat{V}_{TS} + \frac{\beta}{30} [\hat{A}_{TS} - \omega_L \hat{V}_{TM} + \omega_M \hat{V}_{TL}]$$

$$A_{TSP} = \hat{A}_{TS} + \frac{\beta}{30} [-b \hat{A}_{TS} - \omega_L \hat{A}_{TM} + \omega_M \hat{A}_{TL}]$$

$$\dot{\hat{R}}_S = 30 [K_{PS} \epsilon_R + D_{PS}]$$

7.7.2 Traverse Extrapolation

Rev. 6/7/79

$$D_{LP} = \hat{D}_L + \frac{\beta}{30} [\hat{V}_{TL} - V_L - \omega_M \hat{R}_S + \omega_S \hat{D}_M]$$

$$V_{TLP} = \hat{V}_{TL} + \frac{\beta}{30} [\hat{A}_{TL} - \omega_M \hat{V}_{TS} + \omega_S \hat{V}_{TM}]$$

$$A_{TLP} = \hat{A}_{TL} + \frac{\beta}{30} [-b \hat{A}_{TL} - \omega_M \hat{A}_{TS} + \omega_S \hat{A}_{TM}]$$

7.7.3 Elevation Extrapolation

Rev. 6/7/79

$$D_{MP} = \hat{D}_M + \frac{\beta}{30} [\hat{V}_{TM} - V_M - \omega_S \hat{D}_L + \omega_L \hat{R}_S]$$

$$V_{TMP} = \hat{V}_{TM} + \frac{\beta}{30} [\hat{A}_{TM} - \omega_S \hat{V}_{TL} + \omega_L \hat{V}_{TS}]$$

$$A_{TMP} = \hat{A}_{TM} + \frac{\beta}{30} [-b \hat{A}_{TM} - \omega_S \hat{A}_{TL} + \omega_L \hat{A}_{TS}]$$

7.8 Rate Aided Track Computation

Rev. 4/23/79

Rev. 10/12/79

$$\omega_{EC} = W_{SCL} \left[\frac{\hat{V}_{TM} - V_M}{\hat{R}_S} \right] + h_E \text{ (Elevation Positive Up)}$$

$$\omega_{TC} = W_{SCL} \left[\frac{-\hat{V}_{TL} + V_L}{\hat{R}_S} \right] - h_T \text{ (Positive Right)}$$

7.9 Time of Flight Prediction Loop

The time of flight and future range prediction are done according to the logic in Figure A-6 and the equations below.

7.9.1 Air Density Calculation

$$\rho/\rho_0 = 19.605 \frac{P_S}{T_A}$$

7.9.2 Time of Flight

Rev. 4/23/79

Rev. 6/7/79

$$T_V = \frac{R_F (b_s V_B + V_S)}{(b_s V_B + V_S)^2 + \frac{Z_S}{2000} G R_F}$$

$$\Delta T_F = T_V \left(\frac{\rho}{\rho_0} \right) (A_1 R_F + A_2 R_F^2)$$

$$T_F = T_{FO} + C_S (T_V + \Delta T_F - T_{FO})$$

7.9.3 Future Range Vector

Rev. 6/7/79

$$R_{FST} = \hat{R}_S + \hat{V}_{TS} T_F$$

$$R_{F\ell T} = \hat{D}_\ell + \hat{V}_{T\ell} T_F$$

$$R_{FMT} = \hat{D}_M + \hat{V}_{TM} T_F$$

$$R_F = (R_{FST}^2 + R_{F\ell T}^2 + R_{FMT}^2)^{1/2}$$

7.10 Gun Order Commands

Rev. 6/7/79

7.10.1 Gravity Drop Correction

$$G_D = A_3 T_F + A_4 R_F$$

$$R_{FS} = R_{FST} + \frac{G_D Z_S}{1000}$$

$$R_{F\ell} = R_{F\ell T} + \frac{G_D Z_\ell}{1000}$$

$$R_{FM} = R_{FMT} + \frac{G_D Z_M}{1000}$$

$$R_F = (R_{FS}^2 + R_{F\ell}^2 + R_{FM}^2)^{1/2}$$

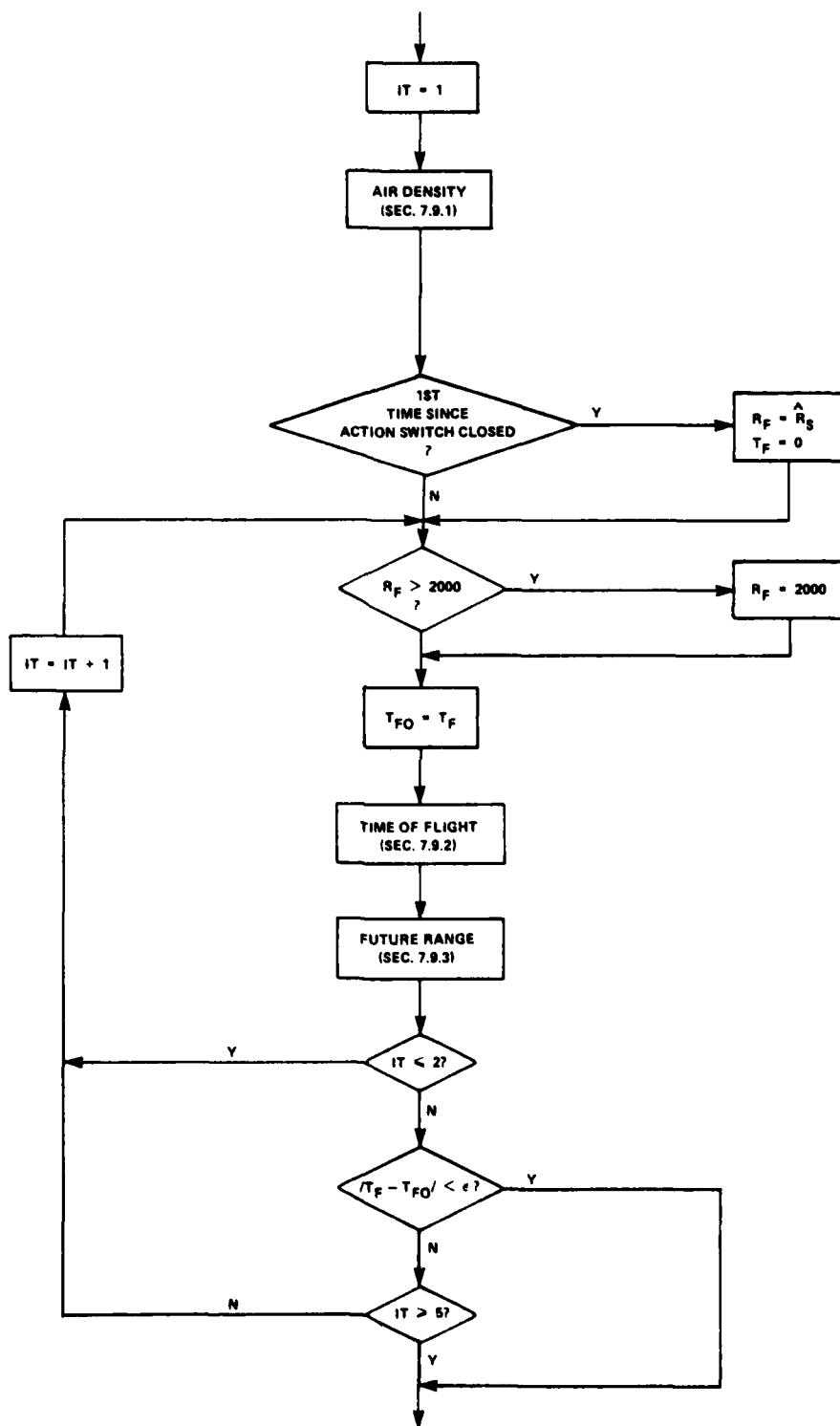


Figure A-6. Time-of-Flight Prediction Loop

7.10.2 Gun Turret Lead Angle Calculation

Rev. 4/23/79

7.10.2.1 Gun Position Vector (slm)

Perform the following computations four (4) times, from top to bottom.

$$b_{SO} = b_S$$

$$b_{\ell O} = b_{\ell}$$

$$b_{MO} = b_M$$

$$b_S = \frac{1}{V_B} \left[\frac{R_{FS} B_V}{R_F} - V_S \right]$$

$$b_{\ell} = \frac{1}{V_B} \left[\frac{R_{F\ell} B_V}{R_F} - V_{\ell} \right]$$

$$b_M = \frac{1}{V_B} \left[\frac{R_{FM} B_V}{R_F} - V_M \right]$$

$$B = (b_S^2 + b_{\ell}^2 + b_M^2)^{\frac{1}{2}}$$

$$b_S = \frac{b_S}{B}$$

$$b_{\ell} = \frac{b_{\ell}}{B}$$

$$b_M = \frac{b_M}{B}$$

$$b_S = b_{SO} + \frac{1}{2}(b_S - b_{SO})$$

$$b_{\ell} = b_{\ell O} + \frac{1}{2}(b_{\ell} - b_{\ell O})$$

$$b_M = b_{MO} + \frac{1}{2}(b_M - b_{MO})$$

$$B_V = ((V_B b_S + V_S)^2 + (V_B b_{\ell} + V_{\ell})^2 + (V_B b_M + V_M)^2)^{\frac{1}{2}}$$

7.10.2.2 Turret Lead Angle

Rev. 10/12/79

After the four iterations of section 7.10.2.1 have been performed, compute the lead angle vector.

$$b_U = -(T_{11} (b_S - 1) + T_{21} b_{\ell} + T_{31} b_M) \quad (\text{Positive Back})$$

$$b_V = T_{12} (b_S - 1) + T_{22} b_{\ell} + T_{32} b_M \quad (\text{Positive Left})$$

$$b_W = T_{13} (b_S - 1) + T_{33} b_M \quad (\text{Elevation Positive Up})$$

7.11 Gun Turret Rate Feed Forward Calculation

7.11.1 Azimuth Lead Angle Trig Functions

$$C_{\lambda A} = \frac{b_S}{(b_S^2 + b_\ell^2)^{1/2}}$$

$$S_{\lambda A} = \frac{b_\ell}{(b_S^2 + b_\ell^2)^{1/2}}$$

7.11.2 Turret Elevation Trig Functions

Rev. 10/12/79

$$T_U = S_U - b_U \quad (\text{Positive Forward})$$

$$T_V = S_V + b_V \quad (\text{Positive Left})$$

$$T_W = S_W + b_W \quad (\text{Elevation Positive Up})$$

$$T_M = (T_U^2 + T_V^2 + T_W^2)^{1/2}$$

$$T_U = \frac{T_U}{T_M}$$

$$T_V = \frac{T_V}{T_M}$$

$$T_W = \frac{T_W}{T_M}$$

$$S_{EG} = T_W$$

$$C_{EG} = (T_U^2 + T_V^2)^{1/2}$$

7.11.3 Rate Feed Forward

Rev. 4/23/79

Rev. 6/7/79

$$\begin{aligned} RFF_A = \frac{1}{C_{EG}} & \left[-\omega_S (C_{\lambda A} S_{EG} C_E - S_E C_{EG}) \right. \\ & - \left(\omega_\ell + \frac{R_{FMT} \dot{R}_S}{\hat{R}_S R_{FST}} \right) S_{\lambda A} S_{EG} \\ & \left. + \left(\omega_M - \frac{R_{F\ell T} \dot{R}_S}{\hat{R}_S R_{FST}} \right) (C_{\lambda A} S_{EG} S_E + C_{EG} C_E) \right] \quad (\text{Positive Right}) \end{aligned}$$

$$RFF_E = \left[-\omega_S C_E S_{\lambda A} + \left(\omega_L + \frac{R_{FMT} \dot{R}_S}{\hat{R}_S R_{FST}} \right) C_{\lambda A} \right. \\ \left. + \left(\omega_M - \frac{R_{F\&T} \dot{R}_S}{\hat{R}_S R_{FST}} \right) S_E S_{\lambda A} \right]$$

(Positive Down)

7.12 Output Fade In Logic

Rev. 6/7/79
10/12/79

This logic is not executed directly after the above section 7.11, but rather after the range gate output. See Figures A-3 and A-5 for further clarification.

$$F(\tau) = \begin{cases} 1.25\tau & \tau < 0.8 \\ 1.0 & \tau \geq 0.8 \end{cases}$$

$$\omega_{EC} = \omega_{EC} F(\tau)$$

$$\omega_{TC} = \omega_{TC} F(\tau)$$

$$\omega_{ECH} = \omega_{ECH} \{1 - F(\tau)\}$$

$$\omega_{TCH} = \omega_{TCH} \{1 - F(\tau)\}$$

$$\omega_{EC} = \omega_{EC} + \omega_{ECH}$$

$$\omega_{TC} = \omega_{TC} + \omega_{TCH}$$

$$b_U = b_U F(\tau)$$

$$b_V = b_V F(\tau)$$

$$b_W = b_W F(\tau)$$

$$RFF_A = RFF_A F(\tau)$$

$$RFF_E = RFF_E F(\tau)$$

Output $b_U, b_V, b_W, RFF_A, RFF_E, \omega_{EC}, \omega_{TC}$.

7.13 Inhibit Fire Light Logic

This logic is specified in Figure A-5.

8.0 MANUAL RANGE MODE

Added 4/4/79

This mode is designed as a simple back up mode in case the laser ranger is inoperative. After entering this mode as depicted in Figure A-3, the following equations should be executed.

8.1 First Time Logic

Rev. 4/23/79

On the initial pass only, perform the following.

$$\begin{array}{ll} b_s = 1 & A_2 = 0.1811 \times 10^{-6} \\ \text{Turn "Inhibit Fire Light" On} & A_3 = 21.3352 \\ A_1 = 0.4175 \times 10^{-3} & A_4 = -0.0221268 \\ G = -9.806 & V_B = 1045 \end{array}$$

8.2 Input Processing

Perform all calculations in Section 7.1.

8.3 Air Density Calculation

$$\rho / \rho_o = 19.605 \frac{P_S}{T_A}$$

8.4 Time of Flight

Rev. 4/23/79

$$\begin{aligned} T_V &= \frac{R_P (b_s V_B + V_S)}{(b_s V_B + V_S)^2 + \frac{Z_s}{2000} GR_P} \\ \Delta T_F &= T_V (\rho / \rho_o) (A_1 R_P + A_2 R_P^2) \\ T_F &= T_V + \Delta T_F \end{aligned}$$

8.5 Gravity Drop

$$G_D = A_3 T_F + A_4 R_P$$

8.6 Future Range

$$\begin{aligned} R_{FS} &= R_P + \frac{G_D Z_S}{1000} \\ R_{Fl} &= \frac{G_D Z_l}{1000} \end{aligned}$$

$$R_{FM} = \frac{G_D Z_M}{1000}$$

$$R_F = (R_{FS}^2 + R_{Fl}^2 + R_{FM}^2)^{\frac{1}{2}}$$

8.7 Lead Angle Calculation

Perform all calculations in Section 7.10.2.

8.8 Rate Aided Track

$$\omega_{EC} = 0$$

$$\omega_{TC} = 0$$

8.9 Turret Rate Feed Forward

$$RFF_A = 0$$

$$RFF_E = 0$$

8.10 Inhibit Fire Light Logic

Turn the inhibit fire light off if the "Gun Error" Flag $\neq 1$ - i.e. the turret is synchronized.

APPENDIX B

**I/O SPECIFICATION
FOR THE
MODIFIED CIU HARDWARE**

1.0 Transfer Functions

1.1 Input Transfer Function (A/D Converter)

±10 Volt dc inputs (max)

input code:	MSB	LSB
(-10V + 1/2 LSB)	1 0 0 0 0 0 0 0 0 0 0 0	0
0	1 1 1 1 1 1 1 1 1 1 1 1	0
(+10V - 3/2 LSB)	0 1 1 1 1 1 1 1 1 1 1 1	1
	1 Lsb = 5mV	

Rev 6/4

When inputting the A/D value by way of the digital input port, the 12 bits of data are left justified in the 16 bit field.

1.2 Output Transfer Function (D/A Converters)

AC/DC scaling output code

	MSB	LSB
(+VRef)	0 1 1 1 1 1 1 1 1 1 1 1	1
(+VRef/2048)	0 0 0 0 0 0 0 0 0 0 0 0	1
0	0 0 0 0 0 0 0 0 0 0 0 0	0
(-VRef/2048)	1 1 1 1 1 1 1 1 1 1 1 1	1
(-VRef + 1 Lsb)	1 0 0 0 0 0 0 0 0 0 0 0	0

Rev 6/4

for AC outputs, VRef = .3 radians
for DC outputs, VRef = +10 Volts

Rev
3/28

The output channel code is appended to the right of the 12 Bit output value, and the resultant 16 bits is output through the digital output port.

2.0 Input/Output Scale Factors (Analog)

2.1 AC input scaling

2.1.1 Sight angles U, V, W

1 V_{RMS} = .865 VDC (fo = 3.5 hz)

The sign is positive when signal
is in phase with reference

Typical signal maximum is 10 VRMS
or 8.65 VDC to the A/D converter

2.1.2 Vertical Reference SinR, CosR, SinP, CosP

Mag Demod converts to DC

10.0 VDC Max

Typical scaling "SinR" = 10 VDC SinR

Polarity Sin P positive up Rev 6/4

Cos P positive up

Sin R positive right

Cos R positive right

2.2 DC input scaling

2.2.1 Total temp T

scale factor = 19°C/Volt

Offset 0.0V = -40.0°C

$T(V_{DC}) = (T-40)(1/19)$

2.2.2 Static Pressure P_s

Scale factor = 1.0 PSI/Volt

Offset 0.0V = 6.0 PSI

$P(V_{dc}) = (P-6.0 \text{ PSI})$

2.2.3 Differential Pressure P_{SID} Scale factor .13 P_{SID}/V

Offset 0.0V = 0.0 PSID

$PSID(V_{DC}) = PSID/.13$

2.2.4 Accelerometers U, V, W Plus ahead

U, V, W = +2.21 V/g Plus right

Plus down

Rev 6/4

2.2.5 Est. Range 0 to 5000 m

+1000 m/Volt

Rev
3/21

2.2.6 Sight Gyro Rates Roll (w_s) +9.95 = 1.0 Rad/sec right

Rev 6/4

w_L +9.95 = 1.0 R/sec up

Rev 6/4

w_m +9.95 = 1.0 R/sec right

Rev 6/4

2.2.7 Reference +10 VDC

2.2.8 Ground 0.0 VDC

2.2.9 Track Stick Commands (Thumb button inputs)

Rev
6/4

H_m Azimuth +10V = 0.25 R/sec Left

H_L Elevation +10V = 0.25 R/sec down

2.3 DC Output scaling

2.3.1 Az turret command +10V = 1.5 R/sec right

E1 turret command +10V = 1.5 R/sec down

2.3.2 Az Sight command +10V = 1.0 R/sec right

Rev
4/2

El Sight command +10V = 1.0 R/sec up

Rev
4/2

2.4 AC output scaling

2.4.1 $\Delta U, \Delta V, \Delta W$ +10 Volts = .298 radians

Rev
6/4

3.0 Laser Interface

3.1 Input Signals from Laser

- Laser Range (Natural Binary Data B0 to B9)
- New Range Data Flag (1 = New, 0 = Old B10)
- Target Insert (Discrete #7, 1 = Laser On, 0 = Off)

3.2 Output to Laser

- Computer Range (Natural Binary Data B0 to B9)

3.3 Scale Factor

- 1 LSB = 5 meters
- 5120m > Range > 150m

3.4 Operational Considerations

- Target Insert indicates an attempt to lase. If Target Insert drops out for more than some specified interval, it should be interpreted as a new range acquisition. For periods less than this interval, a coast mode should be entered.
- New Range Data Flag is the only way one can detect valid range and successful lasing. This bit must be stripped from the range word to be read.
- Range gate functions involve the transition from laser acquisition to laser track. The laser initially acquires targets within the fixed gate of 150 to 5120 meters. If a target is detected, the laser immediately switches to the track mode and requires a range gate for the next laser pulse. The tracking gate is only ± 100 meters and must be supplied by the computer. The range filter value is appropriate, but must be present within the time for the next laser pulse. (100 msec spacing). The laser remains in this track mode until the target insert is deleted and reapplied.

- Coast Logic should be provided to smooth over data missing by either drop-out or to extrapolate between the laser returns to match the computer cycle time. As the computer and laser are asynchronous, the laser must be polled for range data each cycle, and if not present due to drop out or not yet ready, range must be coasted.

4.0 Digital input/output channel assignment *

5.0 Analog input channel assignment *

6.0 Analog input procedure *

7.0 Analog output channel assignment *

8.0 Analog output procedure *

9.0 Discrete input assignment *

10.0 Discrete input procedure *

11.0 Laser input procedure * Modified by Rev 3/21 Sec 3.0

12.0 Interrupt assignment *

13.0 Cold start/warm start procedure *

* Refer to Modified CIU Functional Description Memo
by J. Pintar, E. Fjerstad

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APPENDIX C

MODIFIED CIU FUNCTIONAL DESCRIPTION

COMPUTER INTERFACE UNIT

This document provides a description of the Computer Interface Unit (CIU) as modified for the Air-to-Air Fire Control System. The functional block diagram for this hardware is found in Figure C-1. The Computer-Interface Unit (CIU) provides six functions:

1. Translates aircraft system information into a digital format for use in the general purpose digital processor.
- *2. Performs necessary computational tasks to provide lead angles and lead angle rates corrections to the aircraft weapon system.
- *3. Performs the necessary computations to provide lead angle rates to aid the gunner in tracking a target.
- *4. Provides the laser with estimated range data.
5. Provides a discrete to the sight/turret subsystem to inhibit the firing of the weapon at times when the processor has not arrived at a valid solution.
6. Provides digital data to be recorded on a flight recorder which will aid in evaluating the performance of the airborne fire control system.

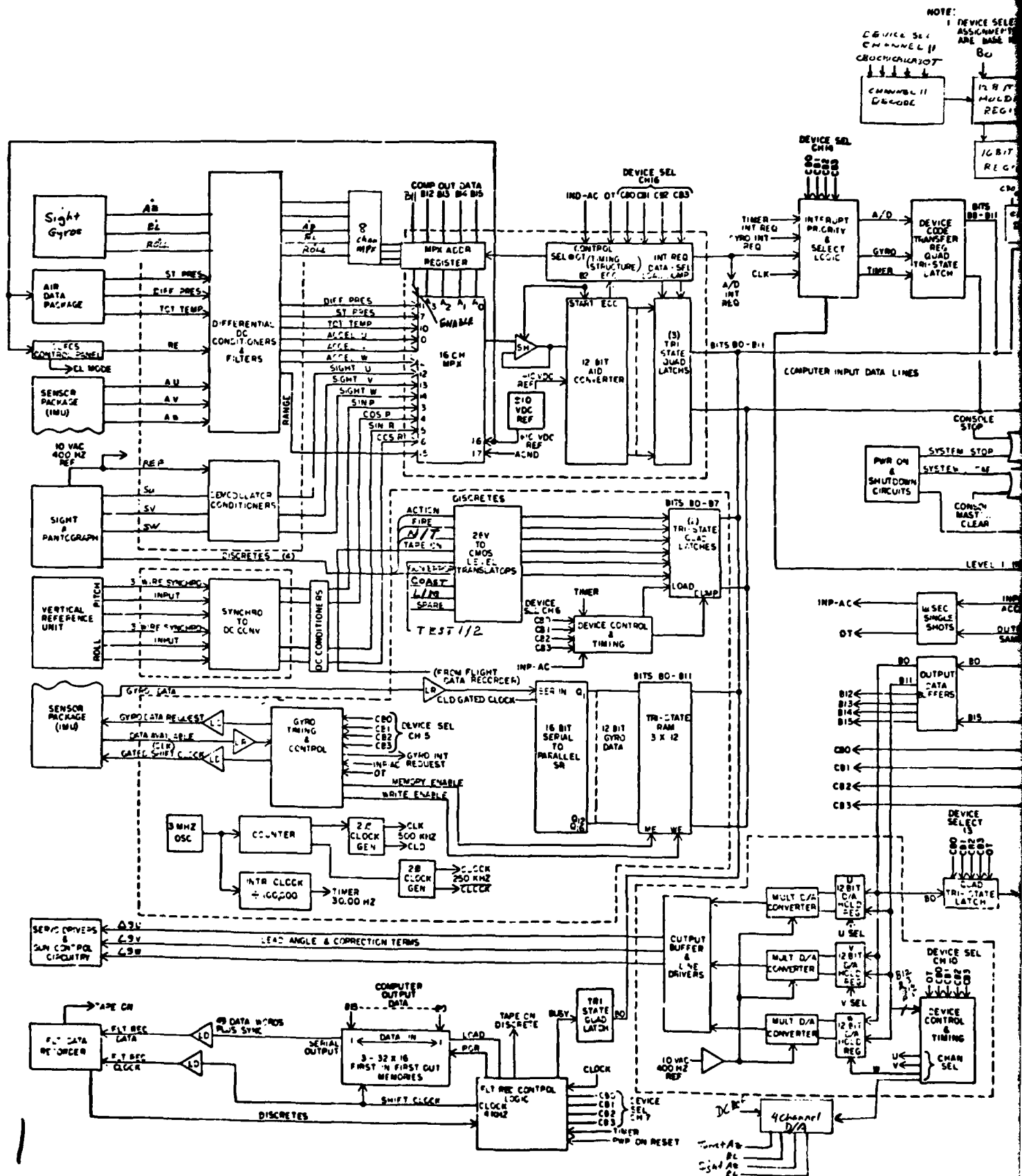
ANALOG SIGNAL CONDITIONING

The aircraft sensors provide various forms of analog signals which must be conditioned and converted to a digital format to be compatible with the general purpose computer. The definition of the analog signal types and their multiplexed analog to digital channel assignments are cited in Table C-1. For the following description, reference may be made to the functional block diagram in Figure C-1.

TABLE C-1. ANALOG INPUTS

CHANNEL NO.	SIGNAL NAME	SIGNAL TYPE
0	Acceleration U	DC
1	Acceleration V	DC
2	Acceleration W	DC
3	Sin Pitch	3-Wire Synchro
4	Cos Pitch	
5	Sin Roll	3-Wire Synchro
6	Cos Roll	
7	Static Pressure	DC
10	Ambient Temperature	DC
11	Differential Pressure	DC
12	Sight U	AC
13	Sight V	AC
14	Sight W	AC
15	Range Estimate	DC
16	10 VDC Reference	DC
17	Analog Ground	DC
*20	Sight Velocity S	DC
*21	Sight Velocity L	DC
*22	Sight Velocity M	DC
*23	Thumb Button	DC
*24	Thumb Button	DC
*25	Spare 3	DC

NOTE: 1. DEVICE SELECT ASSIGNMENTS ARE BASED ON CHANNEL 11 DECODE



The vertical reference signals, pitch and roll, are received in the CIU in 3-wire synchro format. These signals are processed by a 2-channel synchro to direct current sine cosine converter, and the resulting four signals are thereafter treated as DC inputs. This converter utilizes a Scott-T input, thereby offering DC isolation in its interface with the vertical reference.

* The DC signals are received by differential amplifiers utilizing active filters with a break frequency of 3 hertz and a 40 db/decade attenuation. The break frequency, a decade below the A/D sampling rate of 30 hertz, was chosen to minimize measurement errors produced by the aliasing of signal frequencies equal to or greater than one half the sampling rate. The low frequency filters for the three accelerometer signals are resident in the sensor package external to the CIU; within the CIU differential amplifiers utilizing passive T-filters with a 500 hertz break frequency and 20 db/decade slope attenuate line noise that may have been introduced. Range estimate is generated by a manually set potentiometer. Since it is not time-varying, it is given the same DC conditioning within the CIU as the accelerometer signals. The sight rates are conditioned in the same manner as the accelerometer inputs. The three AC signals from the sighting station are first buffered by differential amplifiers, then converted to DC through a phase sensitive demodulator. The signals are then conditioned by active filters similar to those for the DC inputs, attenuating the demodulator ripple by 130 db.

A/D CONVERSION

* The twenty analog signals in buffered DC format are tied to the inputs of a twenty-four channel multiplexer. In addition an internal 10 volt DC reference and analog ground are tied to two multiplexer channels for test purposes. Any of the twenty-two signals may be made available to the sample and hold amplifier input to the A/D by software control. The

appropriate five bit code representing the octal multiplexer channel number is output from the digital processor (CDC 469) on output data lines bits 11 through 15, and Device Code 16B is addressed. The sample and hold then samples the desired input, and makes its analog value constant long enough for the successive approximation A/D converter to make its conversion. The converted digital value is then clocked into a set of tri-state latches to be made available to the CDC 469.

DISCRETE INPUTS

At the beginning of each computer iteration (1/30 second) the Interrupt Clock sets the present values of the Discrete Inputs into a set of tri-state latches. Since the discretes are at various levels at the input to the CIU, each requires a lever translator prior to being fed to the tri-state latches. The CDC 469 packs the discretes into the first eight digits of a computer word. The assignment of the bit locations for the discrete word is given in Table C-2.

ANGULAR RATE INPUTS

Aircraft angular rates are presented to the CIU from the Inertial Measurement Unit (IMU). The IMU utilizes three rate integrating gyros aligned along the aircraft body axes. Each gyro is in a pulse torquing loop with pulse rate a measure of inertial rates and pulse count a measure of angular position. The net clockwise/counterclockwise pulse count is stored in a counter. Upon request from the CIU, the IMU will sample all their counters, store this information in a transfer register, reset the counters to zero, and signal the CIU that the data is available. The data available signal initiates three 16-bit data word transfers, the 12 least significant bits of each being tangible gyro data. The transfer of data from the IMU to CIU is made in serial format at a 500 kHz clock rate. Once the first word is received at the CIU, it is stored in a random access memory (i.e., external to the CDC 469) and the second transfer begins. This process is again repeated and finally the data is transferred from the random access memory to the CDC 469 in three input operations.

TABLE C-2. DISCRETE INPUTS

BIT LOCATION	SIGNAL NAME	LOGIC INVERSION	DESCRIPTION
0	ACTION	Yes	Indicates that gun is being commanded to follow sight.
1	FIRE	Yes	Indicates that weapon is firing.
2	TEST 1/2		Indicates which test mode is being used.
3	TAPE ON	Yes	Indicates that flight recorder is in motion. CIU hardware delays discrete by 2 sec. to allow transport to achieve regulated speed prior to recording.
4	NORMAL/TEST		Indicates whether computer is in normal or test mode.
5	GUN ERROR	No	Indicates that gain is not servoed to commanded position or that computer has not arrived at valid solution or that computer is signaling gunner to break track.
6	TARGET INSERT	Yes	Indicates that laser is off or on.
7	NOT USED		

CDC 469/COMPUTER INTERFACE UNIT COMMUNICATION

A conventional interrupt system with the CDC 469 initiating all service has been utilized to control the data flow between the general purpose digital processor and the CIU interface circuitry.

In the previous sections, it was simply stated that data was transferred to the processor. To understand the mechanism of this operation, a discussion of the first iteration following a power-on situation will follow.

Once power is applied to the system, a master clear pulse from the CIU forces the CDC 469 to its starting address where a short power-on routine initializes the processor to the correct program location. At the same time a power-on reset pulse within the CIU conditions its interface boards to the start condition. The CDC 469 has two preset starting addresses. Normally the processor goes to the cold start starting address 10400. However, at power-up a timer in the CIU hardware detects whether the power had been interrupted for greater or less than 2.5 seconds. For an interruption of less than 2.5 seconds, the CIU activates the alternate starting address line to the CDC 469, and the processor is forced to location 11000.

A countdown of the CIU 3 MHz oscillator is now underway, and 1/30 of a second later the 30 hertz interrupt clock generates an interrupt request. Upon recognition of this interrupt, the processor begins its computational tasks. For a cold start situation, the first software task is to time out a delay of 150 iterations of the 30 hertz interrupt clock, or 5 seconds. This delay allows time for the gyros in the IMU to spin up to speed.

All interfacing service is initiated by the processor; at a time determined by the processor software, a request for I/O data is made. The interface system responds to this request by initiating one of several operations depending on which data is requested.

The request for A/D data is accomplished by selecting the A/D device controller which is assigned DEVICE SEL 16, using an output data instruction. The data transferred to the A/D selects the desired multiplexer channel to be converted, and initiates the conversion process. Once this output instruction is completed, the processor is free to return to computation. The conversion of one piece of A/D data will now take 100 μ sec to complete, and upon completion a request for service will be sent to the processor using a level one interrupt, and the interrupt code for the A/D converter, listed in Table C-3, is loaded into the device code transfer register. Upon answering the interrupt request, the processor reads the transfer register, detects which driver interrupted it, and jumps to the service routine for that device, which in this case is the A/D converter. The data is then read from the A/D and the service request is reset. After completion of the service routine, the processor will return to its normal computational mode. The software may initiate another A/D data request, or, if the 16 word A/D data buffer is satisfied, gyro data from the IMU may now be requested. The servicing of the gyro's is similar to that of the A/D with the exception that three 16-bit words will now be taken sequentially.

The interface system was designed and built with a three level priority technique which complied with Control Data Corporation documentation. The system would handle simultaneous interrupt requests with the following order of hardwired priority:

1. Interrupt Clock
2. Gyro
3. A/D Converter

For other than simultaneous requests, the devices are serviced on a first come, first serve basis. In either event, overlapping service requests are stored in the interface logic until service is available. However, contrary to CDC documentation, the CDC 469 will not handle any service request if there is another interrupt pending. Therefore it is

imperative that the software be designed to guarantee that each interrupt be serviced before another is initiated. In addition to the A/D and gyro inputs are the discrete inputs. Since all discrete data (Table C-2) is packed into one 16-bit word, it need not operate on an interrupt basis. Shortly after the interrupt clock is serviced, the software selects the discrete device (channel 6) and reads the data which has been clocked into a storage register.

The functional block diagram of Figure C-1 shows that the data transferred to the processor is organized on a common bus system. Each input device, i.e., the A/D, laser, gyros, discretes, and transfer register, places its data on this bus through tri-state quad latches which only become active when that particular device is selected. The CIU utilizes twelve of the possible 16-bits of the input data bus, with the remaining four bits forced to zero by means of open circuit logic convention.

TABLE C-3. INTERRUPT REGISTER CODE

INTERRUPT NUMBER	DEVICE	INTERRUPT CODE			
		B9	B9	B10	B11
220	A/D Converter	1	0	0	1
240	Gyro Inputs	1	0	1	0
300	Interrupt Clock	1	1	0	0

D/A CONVERTERS

The D/A converters translate the digital solutions of lead angles and rates to analog signals required by the sight and turret. Each converter is selected by device code 10 per (Table C-4) and bits 12-15 of the output data word per Table C-5. The selected converter stores the output data in a 12 bit holding register and within 10 usec converts this data to a scaled amplitude signal.

RANGE DATA

The laser provides the CIU with range data used in performing its computation and the CIU provides the laser with an updated range gate for the next laser range measurement as shown in Figure C-2. The range gate is provided by the CIU to the laser in the form of a 32-bit word accompanied by a 160 kHz clock and a word sync pulse. The data word consisted of 10-bits of range data (LSB first) followed by 22 zeroes. The falling edge of the clock is synchronized with each data bit. The word sync pulse is one data bit long and occurs at the 32-bit time of the data word. At a time controlled by the software updates to the range gate are made by selecting I/O channel 11 and transferring the new estimated range data into a holding register. The transfer of the new data into the parallel to serial register occurs on the next RWSP pulse following the update.

When the laser has found a target within the range gate window the laser provides the computer with measured range data in the form of a 32-bit digital word preceded by a Range Ready Synchronized to Computer Clock (RRSCC). The valid range data is contained only in the first 10-bits (LSB first) of the word, with the remaining 22-bits being zeroes. The RRSCC is delayed one word time by the CIU to provide an enable for clocking the first 16-bits of the range data into a holding register. The ten bits of data is clocked into the tri-state latches by RWSP.

One additional bit of information is provide the computer to indicate when the data is new or old. This latch is set to a one with RRSCC and reset when the register is polled.

TABLE C-4. I/O CHANNEL CODE ASSIGNMENTS

CHANNEL NUMBER	DEVICE	CHANNEL CODE			
		CB0	CB1	CB2	CB3
0	Video Monitor	0	0	0	0
1	Programmer's Console	0	0	0	1
2	Teletype (Print)	0	0	1	0
3	Teletype (Keyboard)	0	0	1	1
4	Memory Loader	0	1	0	0
5	Gyro Inputs	0	1	0	1
6	Discretes	0	1	1	0
7	Flight Recorder	0	1	1	1
10	*D/A Channels	1	0	0	0
11	*Computer Range Data	1	0	0	1
12	*Laser Range Data	1	0	1	0
13	Fire Inhibit	1	0	1	1
14	Interrupt Register	1	1	0	0
15	(Spare)	1	1	0	1
16	A/D Converter	1	1	1	0
17	(Spare)	1	1	1	1

TABLE C-5. D/A CHANNEL ASSIGNMENTS

CHANNEL NO.	B12	B13	B14	B15	TYPE
0 GUN POSITION U	0	0	0	0	AC
1 GUN POSITION V	0	0	0	1	AC
2 GUN POSITION W	0	0	1	0	AC
3 SIGHT R.F.F. EL.	0	0	1	1	DC
4 SIGHT R.F.F. AZ.	0	1	0	0	DC
5 GUN R.F.F. EL.	0	1	0	1	DC
6 GUN R.F.F. AZ.	0	1	1	0	DC
7 NOT USED	0	1	1	1	----

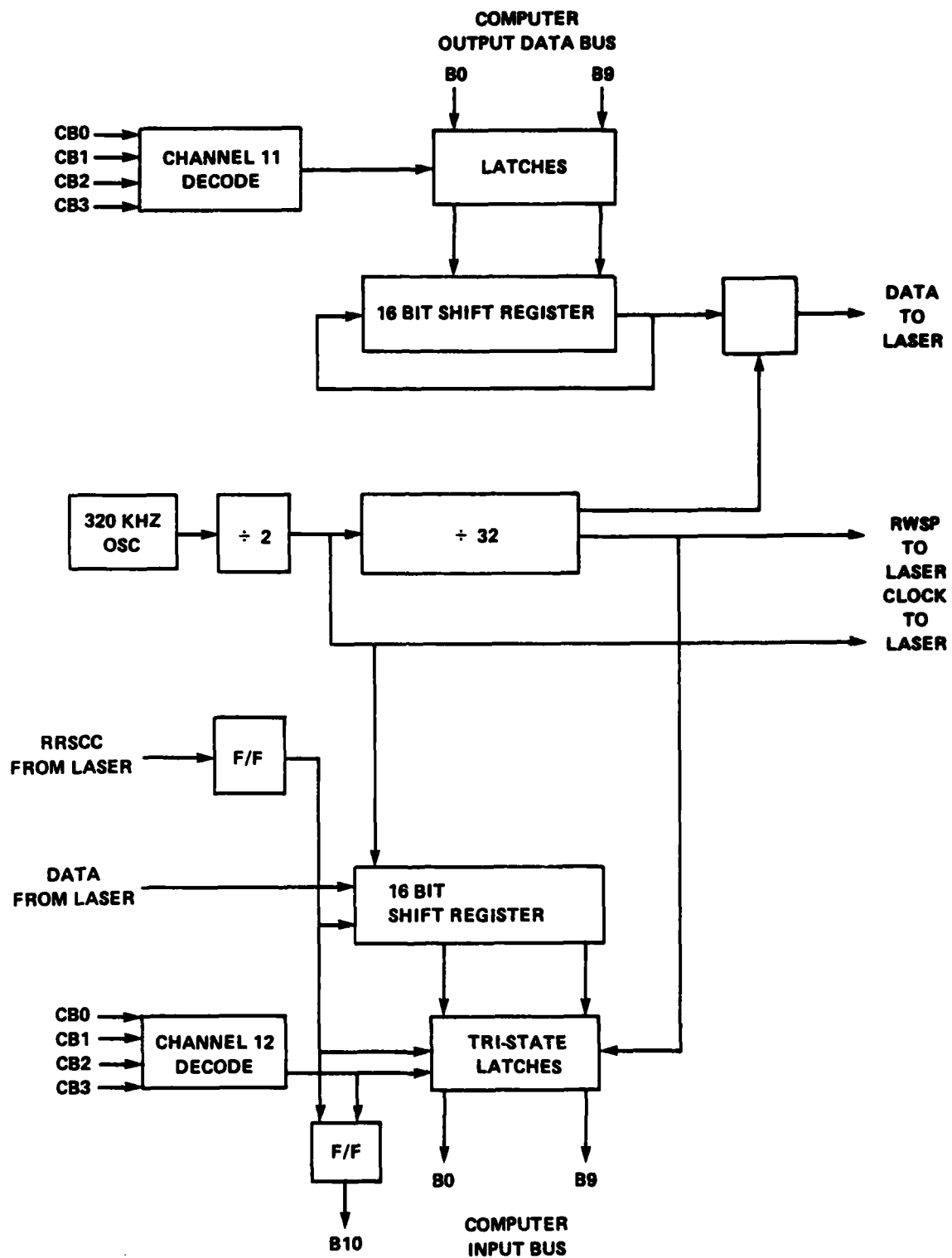


Figure C-2. Laser Interface Block Diagram

The laser data is provided to the CIU in a manner that is asynchronous with the 1/30 sec timer. To avoid possible interrupt conflicts the laser data is retained in the register and the register is polled every 1/30 sec by the software by selecting I/O channel 12.

FLIGHT RECORDER

The CIU has a subfunction of data logging such that a selected set of parameters may be recorded in flight for use in the system evaluation and/or troubleshooting. The selected data is transferred from the processor to first in - first out (FIFO) memories. The transfer from the FIFO's in the CIU to the government furnished flight recorder is set at a bit rate of about 4 kHz, or 4 msec per 16-bit word. Weighing this rate against the 30 Hz processor iteration rate and the available software space, a limited flexibility in recording mode relating recording rate to number of variables recorded was established. In software controlled Mode 0, seven parameters from one iteration are stored in a software buffer, followed by the same seven parameters for the next iteration. After the seventh iteration, the 7 x 7 or 49 words plus an index code word (record marker) are transferred to the FIFO's at a rate of about 2.5 μ sec per word, or 125 μ sec total. The FIFO then shifts out data serially to the recorder taking about 6 processor iterations to complete the 50 word record. A clock gap then appears on the data line indicating the end of the record, then at the beginning of the 8th iteration, when the FIFO's are loaded with another 50 words, another shift out occurs. Mode 0 is assumed in the software assembly. If Mode 1 is desired, a key-in must be executed from the console after the assembly has been loaded. In Mode 1, 49 words from one iteration are transferred to the recorder every 7 iterations, resulting in an increased number of parameters measured at the expense of sampling rate.

PROGRAMMER'S CONSOLE TO PROCESSOR BUFFERING

The CDC 469 processor utilizes C-MOS drivers for its data and control signals, so provisions are necessary for operation in the console controlled mode with the long cables inherent with flight line conditions.

Each cable connection from the processor to the programmer's console, and vice versa, includes a line driver/receiver pair, with one half of the pair resident in the CIU and the other in the Console Interface Unit, which is mounted in the console cabinet. Provision is made to deactivate the receivers in the CIU during normal operation so that the undriven inputs will not interfere with proper operation.